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Comparing Economic, Environmental, and Social Effects of Central Air Conditioner Size and Thermostat Schedule Interactions

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M.S. DEGREE THESIS

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COMPARING ECONOMIC, ENVIRONMENTAL, AND SOCIAL EFFECTS OF CENTRAL AIR CONDITIONER SIZE AND THERMOSTAT SCHEDULE INTERACTIONS

A Thesis

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Sustainable Engineering

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ABSTRACT

Selecting the capacity of a central air conditioning (AC) system is based on a long list of structural factors within a home, but is normally chosen without considering effects on stakeholders outside of the home. Energy use by residential air conditioners is relevant to consumers as an expense, but also to utilities as a contributor to peak demand and to society by the resultant carbon dioxide and other emissions. In this article, we investigate how size and operational patterns of central residential air conditioners interact with stakeholder benefits and costs. The case study analyzes energy use for systems sized from 3.0-5.5 tons in single family homes in Phoenix, Arizona and quantifies the costs and benefits to homeowners, electric utilities, and society. For homeowners, larger units are preferred due to lower energy consumption, leading to lower net costs, and the ability to cool the house quickly. However, under the same conditions, a smaller AC system can provide double the potential profit to the utility from reduced generation and peak load costs. As a result of lower energy consumption, larger units have lower environmental externality costs from carbon and criteria pollutant emissions. However, a social perspective that considers homeowner, utility and externality costs together results in an overall preference for smaller units with setback schedules, driven by the value of peak demand reduction.

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This document has taken a village to write and edit, ideate and solidify, cry and leap for joy.

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To my family and friends, thank you for lending your ears and editing skills and helping me see it through. You are the best!

Sometimes in the early morning on my way to class, I walked past the sign for Kate Gleason College of Engineering. I could hardly believe I had the honor to enter these halls, after dreaming of becoming an engineer for many years. Addressing the KGCOE students on stage at graduation was the first time I truly believed it. Thanks again to all of you who have helped me on my way.

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1. Introduction

The number of U.S. homes with central air conditioning (AC) grew from 68% in 1993 to 87% in 2009. These homeowners spend $11 billion on air conditioning each year [1], [2] corresponding to about 13% of their household energy consumption. In addition to economic costs, there are environmental impacts from the pollutants released due to electricity generation. The average central AC system uses 2,000 kWh annually, with consequential emissions of 3,500 pounds of carbon dioxide and 31 pounds of sulfur dioxide [3]. These and other pollutants are associated with measurable human health effects. The aggregate of homes with air conditioning also contributes significantly to electrical loads. In warmer climates such as California, 30% of the peak electricity demand during the summer months is created by air conditioning use [4]. These economic, environmental, and social effects will continue to grow, as almost 90% of newly built homes in the U.S. have central AC [2].

The size of an AC system and its thermostat schedule, i.e. its operational pattern based on user preferences, jointly affect energy consumption and consumer costs. A large capacity central AC system maintaining a constant temperature in the home has the potential to consume more energy than a smaller one since it has a higher rated power. However, the amount of energy consumed depends on its operational pattern, which in turn is determined by its thermostat setting. Additionally, AC systems are often oversized, leading to various inefficiencies and wasted energy. The benefits of a larger AC include faster cooling whereas the benefit of a smaller unit includes lower capital cost and lower peak demand. For example, a homeowner with a smaller system that turns off the AC while away must wait longer for their living space to return to their desired temperature when they return. Although these general trends are understood, the tradeoffs between the larger and smaller capacities have not been quantified. The additional layer of homeowner's thermostat schedule further complicates the tradeoffs. Current AC sizing guidelines do not consider these tradeoffs, nor do they consider the impacts to the major stakeholders from the three-dimensional sustainability (social, environmental, economic) point of view.

This research investigated the interaction between the capacity of a central air conditioning system, thermostat schedule and set point temperature for Phoenix, AZ. The results revealed the AC size and schedule combination that realized optimal economic, environmental and human health outcomes for three main stakeholders: the electrical utilities, society, and the residential consumer.

2. Problem Statement & Purpose

AC sizing and selection guidelines do not consider the interactions between size, operational pattern, peak load costs, and environmental and social impacts, nor do they consider the impacts on the major stakeholders. Bichiou et al. found that "very limited studies have been reported to select HVAC system design features and its operation settings" [5]. This research aims to close a piece of that gap. The following sections review previous research around this topic. As Solaimani et al. noted, in order to motivate energy reduction, more research exploring the role of each stakeholder is needed [6]. Expanding the selection criteria of power-hungry equipment is needed, given the context of climate change and increases in renewable energy sources that can destabilize the grid.

AC size and thermostat schedule interact in a variety of ways. For example, larger AC systems initially cost more, but enable faster temperature control with shorter duty cycles. Small air conditioners cost less upfront, but have less flexible thermostat scheduling ability because they take longer than a larger system to cool a given load. A homeowner using setbacks must set a desired temperature earlier in the day for a smaller system to reach that temperature. Smaller systems run for longer at lower power than that of a larger system because they take longer to reach a desired temperature. However, a small unit may be inefficient at cooling the house. If a smaller system is recommended for a home and the consumer will save money by using a certain thermostat schedule, what will be the associated burden placed on the transmission and distribution (T&D) utility and power generators? These smaller units consume more energy over time than larger ones since they must run for longer, meaning more electricity will need to be produced. What health costs are associated with this choice? Emissions change depending on the energy mix of the region as well as the amount of electricity consumed and the time at which it was consumed. The answer to these questions can inform decisions made by each stakeholder to reduce costs and undesired effects. For example, potential policy by way of subsidies or other incentives will be explored for the utility stakeholders.

The purpose of the research developed and presented in this thesis is to identify the tradeoffs between economic and environmental outcomes depending on an AC system's capacity and thermostat schedule. This work explored how the combinations of various AC capacities and thermostat set points affect energy consumption from the centralized grid. In order to motivate energy reduction, more research exploring the individual role surrounding each stakeholder is needed [6]. The homeowner is the first stakeholder. The power generation utility and transmission and distribution (T&D) utility are treated as another stakeholder. The third stakeholder is society as a whole. The thesis research considered each stakeholder's priorities to fill knowledge gaps in both economic effects and avoided emissions. Results will be in terms of factors such as human health costs, private costs, effects of peak usage, and marginal environmental emissions.

Electrical grid customers determine electricity demand and must be motivated to reduce energy use on the grid [6]. This research provides homeowners an understanding of initial investment value. The results also reveal how to program and choose the type of thermostat given an AC size as well as how to choose the AC size given thermostat scheduling preferences. Although the scenarios that save the most energy may be obvious, the lifetime costs and tradeoffs between money and comfort is not. By understanding these interdependencies, consumer motives can be leveraged. Utilities benefit through demonstrated rebates on AC capacities that can decrease their costs and increase net revenues.

3. Background

In this section, homeowner energy demand and consumption is explored in terms of AC usage as well as the utility's role in peak power production, management, and attempts at curtailment.

3.1 The State of Central AC in the Home

The following sections explore the role of central AC use in residential U.S. homes within the context of overall energy consumption as well as how thermostats influence consumption. Similarly, there is a discussion on how the capacity of a household's AC system is typically determined, as this is one of the two main parameters analyzed in the research.

3.1.1 Energy Consumption

One-fifth of the US housing stock, or 11.9 million homes, were built in the 1980s [7] and have AC equipment over 20 years old. These older systems have lower efficiencies, which increases energy consumption. Even houses with AC systems that are just 10 years old could be saving as much as 20-40% on their energy consumption by using a newer model [3]. This increase in cost does not include the impacts associated with the construction of older homes, which tend to leak conditioned air more than newer homes. To curb these inefficiencies, the Environmental Protection Agency (EPA) and Department of Energy (DOE) as well as state governments have mandatory energy standards for new homes. Energy efficiency is further impacted because only 42% of homes using AC perform regular maintenance on their equipment [2]. Electrical energy consumption from AC systems is also determined through efficiency characteristics. For example, increases in recirculation rate, supply and return duct leakage, fan power draw, and relative humidity increase the operating time of the equipment, which is the ultimate driver of electricity consumption [8].

3.1.2 Current State of AC Sizing

The size, or capacity, of AC equipment plays a major role in energy consumption. Most ACs have a fixed capacity, or amount of cooling they can provide. One standard method to size ACs comes from the Air Conditioning Contractors of America (ACCA). The latent (wet bulb) load is calculated and added to the sensible (dry bulb) cooling load for the house, generating what is called the Manual J value. ACCA's Manual S makes the final suggestions of AC size using the Manual J value, target air flow, performance data for the possible equipment and finally the outdoor and indoor design temperatures as inputs. The ACCA Manual J calculation attempts to design a central air conditioning system and recommend an AC capacity that will cool the home for all but 1%, or 88 hours, of the year given a location's typical 30-year hottest temperature. This method is widely used as the national standard either alone or as a basis for a contractor's calculations.

Before government standards became stricter, Heating Ventilation and Air Conditioning (HVAC) contractors developed their own rules-of-thumb to choose how large of a system will provide sufficient cooling to the house. Many contractors still use these self-developed guidelines [9], one reason being to avoid customer callbacks. When these practices take place, oversizing occurs most of the time [10]. Oversizing can also be due to contractors adjusting their calculations to be closer to the generic "400 square feet" rule-of-thumb that designates one ton or 12,000 Btu-hours of air conditioning capacity will cool about 400 ft^2 [9]. Further overcorrection occurs when a contractor adjusts for poor construction that does not meet building codes. ENERGY STAR notes that improperly oversized ACs are "recognized as a common industry problem" [11]. ENERGY STAR's manual on correctly sizing ACs explains that oversized units lead to more expensive initial and lifetime costs. Systems are less frequently undersized, leading to other problems such as insufficient cooling capacity and decreased comfort. An example of how sizing affects indoor temperatures is seen in Figure 1 and Figure 2 generated using the BEopt software discussed in the Literature Review. The graphs of temperature over time show the simulated difference between a given cooling load as handled by a 4-ton AC system and a 2-ton AC system respectively. Both used a programmable thermostat schedule with 76°F set point and 85°F setback during 8am-5pm. Figure 1 and Figure 2 are plotted by scheduled temperature in yellow and actual indoor temperature in blue. Notice how the 2-ton unit takes longer to reach the desired set point temperature.

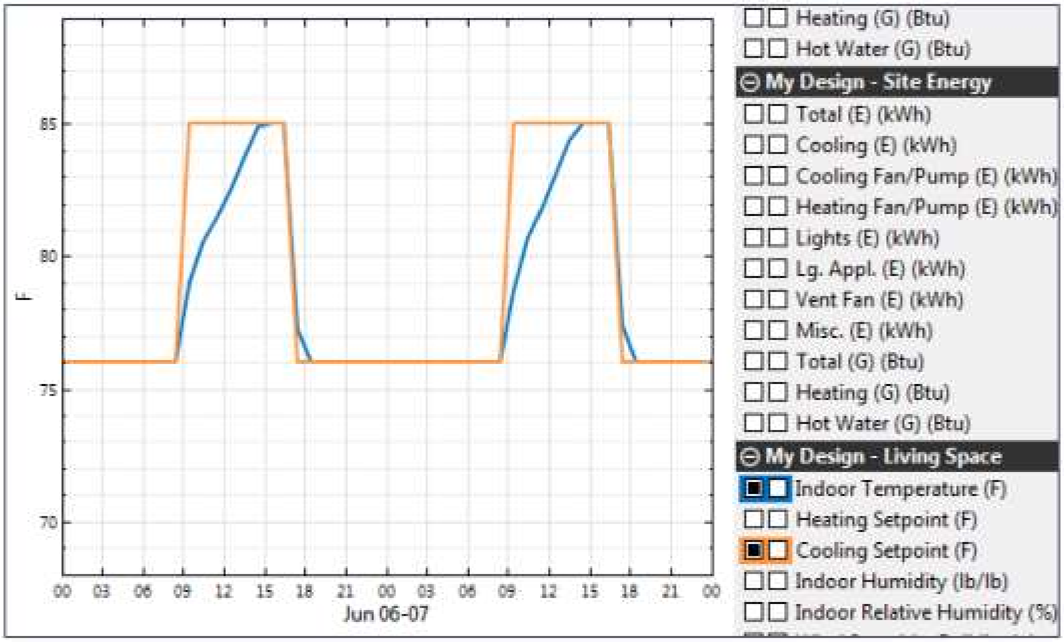

Figure 1: A 4-ton AC system, indoor temperature versus cooling set point over one summer day

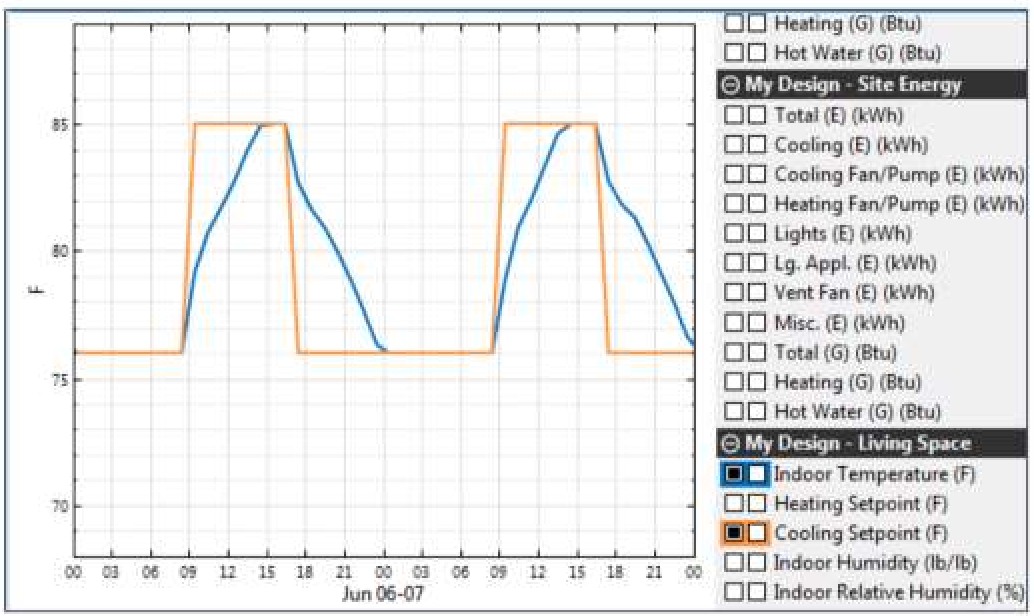

Figure 2: A 2-ton AC system, indoor temperature versus cooling set point over one summer day

3.1.3 Role of Thermostats and AC system Efficiency Characteristics

The thermostat set point, or desired temperature, is an important metric by which the consumer can influence the amount of energy consumed. Historically, a user sets a manual thermostat at the desired temperature for the living space and the AC will cool until reaching it. To maintain the temperature, the unit will cycle on and off. The length of time for which the AC runs is called its duty cycle.

With programmable thermostats, users have the option to create programs, or schedules, in which the set point will change at specified times and dates. The thermostat follows predetermined set point guidelines based on the sensed environment. In the U.S., programmable thermostat usage is split mostly by region. Of the 38% of homes that have programmable thermostats in the warmer south, 67% use their central AC every day during the summer [2]. Unfortunately, research has shown that a consumer owning a programmable thermostat does not mean that the thermostat is used correctly or even at all. Pritoni et al. used a crowd sourced online survey, asking participants to upload photos of their programmable thermostat to prove their actions were consistent with reported behaviors. The researchers found that one-third of participants did not use the programming capacity of their thermostat. Misuse of the thermostat was prevalent. Examples included incorrect current time and date thereby nullifying the effects of the thermostat schedule, confusing the current temperature of the room for the set point temperature on the display, or accidentally placing the thermostat on “hold” when reporting that it was set to a program. A “hold” is when the user overrides the system’s programmed thermostat schedule manually. This action keeps the desired temperature at a constant degree until the user manually removes the “hold”. Consumers often don’t understand how AC technology works. One-third of participants in the study believed the myth that setting back the temperature when no one is home during warmer months uses more energy than holding at a constant lower temperature [12]. The authors ended their paper by estimating that internet-connected programmable thermostats are installed in over 4 million North American homes and that the number of misused thermostats will continue to grow, an important insight given the next topic.

More recently, smart thermostats have appeared on the market bringing more energy savings potential than their predecessors [13]. This technology allows users to switch the set point remotely from a smartphone or computer. The technology aligns the thermostat schedule more closely to the user’s habits. One type of smart thermostat called a learning thermostat, such as Google’s Nest, learns user-preferred behavior and self-corrects. Smart thermostats also attempt to optimize thermostat schedule based on external inputs of electricity price to assist the user in avoiding costs. These optimizations can be manually overridden at any time by the user. Additionally, smart thermostats assist with the problems associated with programmable thermostats by providing transparency and higher usability to increase user comprehension, these features can help the user take advantage of the benefits provided by a programmable thermostat.

3.2 Peak Power and Peak Power Management

AC is often used during the electrical grid’s peak demand times. However, not only are ACs used during peak demand, they are a large contributor to its origination. Figure 3 depicts the hourly actual load for western New York State over the year 2015 [14]. This data was chosen as it is more readily available than other locations. The figure shows that not only is there more load in the warmer summer months, but the peaks are higher as well. Electricity use during this time contributes to higher impacts on the environment and a transmission and distribution utility's bottom line. The impact on the utility is so great that utilities use various means to avoid consumption and lower the need of a power generator utility to generate electricity during this time. The reasons for this are discussed in the following subsections. An example of a utility's peak demand avoidance using demand response (DR) programs is also detailed.

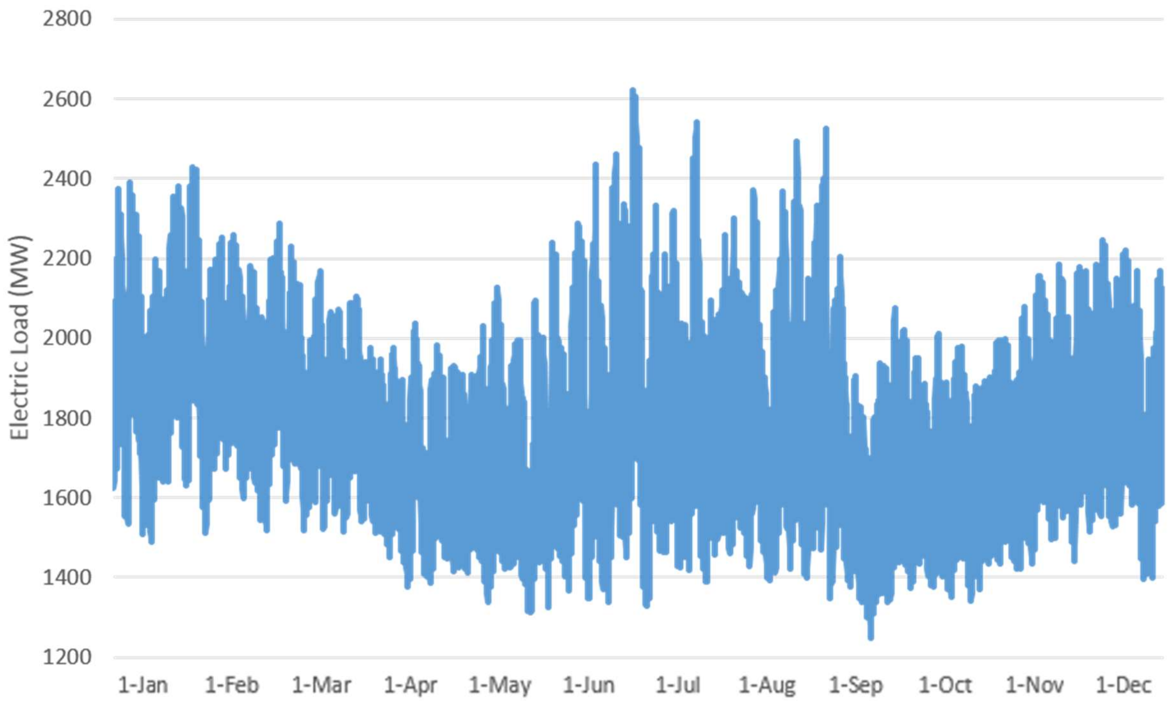

Figure 3: 2015 Hourly Load for Western NY

3.2.1 Peak Power

Different types of electricity generators, or power plants, are used throughout the day to meet shifts in demand. Baseload power plants typically use coal or nuclear energy as a fuel source. Generators using these fuel types do not ramp up or down quickly and therefore typically run continuously around the same production level all day to provide a constant electrical capacity on the grid. When demand for electricity increases, other types of power generators kick on line [15]. Peak power refers to the electricity consumed or generated during peak demand times on the grid. Peak times usually occur from early afternoon through the early evening as people return from work. These two types of loads can be seen in Figure 4. Peaker power plants have the highest operating cost per kWh of any power plant because they are not used often, use more expensive fuels, and are less efficient [16]. Utilities do not want peak demand because it makes the grid less stable and increases the chance of outages. To keep the grid stable, the electrical grid is built to have a larger capacity than necessary, leading to environmental burdens [17]. Since peak power is also more expensive to generate, those increased prices and environmental burdens are passed to the customer.

The activity for this period is especially high during the summer months when homeowners turn on their ACs or lower their thermostat settings in anticipation of returning home. For example, in Texas two-thirds of electricity use (peak and non-peak) in the summer is from AC usage [18]. This high use creates a higher demand on the grid [15]. There are dedicated power plants, called peaker plants that are used to increase electrical generation to meet peak demand.

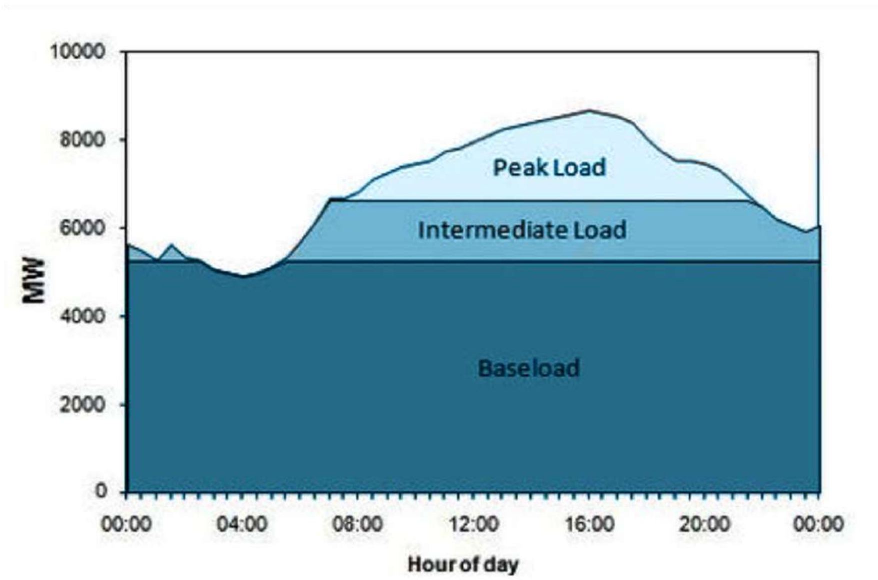

Figure 4: Example of peak power over 24 hours [15]

Larger capacity AC systems have higher instantaneous power draw and the potential for higher peak load costs to the electrical utility. On the other hand, a smaller AC system may have a lower price tag and lower peak load costs, but be less energy efficient. Two AC systems with the same energy efficiency use the same amount of electricity to remove a unit of heat from the home. For example, a 4-ton unit is rated to remove 48,000 Btu per hour while a 2-ton unit is rated to remove 24,000 Btu per hour. If the two units have the same energy efficiency, each will use the same amount of energy to remove a quantity of heat, although at different rates. The amount of electricity consumed by an AC system also depends on its usage over time, as determined by thermostat settings. A homeowner with a smaller unit who turns off the AC while away will save on electricity bills but must wait longer for their space to reach the desired temperature when they return (Figure 5). In Figure 5, the thermostat is set to 70°F from 6pm - 8am and turned off while unoccupied during the day. Larger systems demand more power when turned on but quickly decline in hourly energy consumption because they reach the cooling set point faster than the smaller unit. Since smaller systems are unable to cool quickly, their peak consumption period is lower but spread over more time.

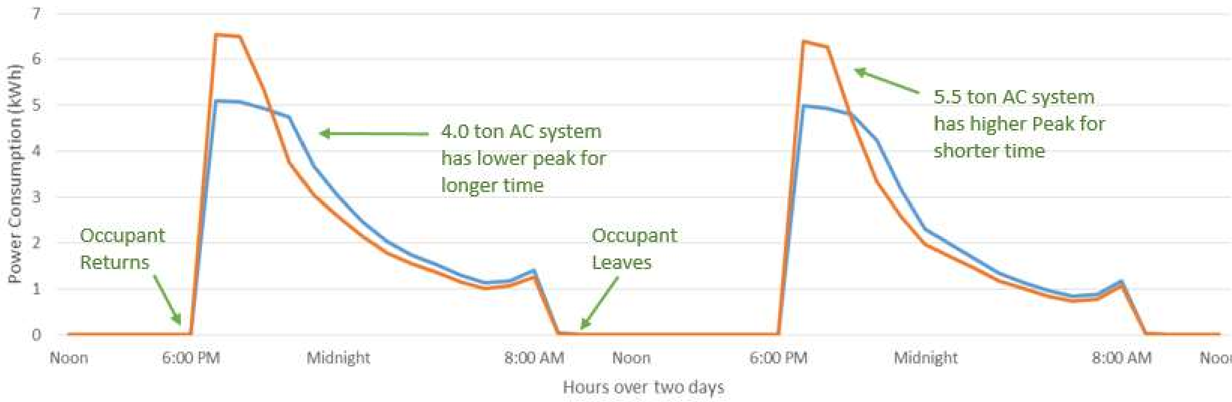

Figure 5: Using large (5.5 ton) and small (4.0 ton) capacity AC systems, average hourly energy consumption is shown over a typical 2-day period (June 4-5) in Phoenix, AZ.

3.2.2 Load Shedding & Load Shifting

To manage peak demand, a strategy called peak shifting or load shifting can be used. Load shifting is when the load usually needed during peak time is demanded at a different time [17]. One way to shift load from an AC during peak times is by precooling the home, simply meaning that the house is cooled ahead of peak demand. Precooling is more efficient in terms of reducing peak power demand and therefore avoids environmental impacts due to power generation infrastructure and extra energy production [17]. Load shedding is when the load during that time is no longer demanded.

3.2.3 Demand Response

Reducing peak demand is advantageous for utilities. Money is saved by avoiding costs of new infrastructure and upkeep of facilities reserved for peak hours [19]. T&D utility companies use demand response programs to initiate load shedding. One type of demand response program is when utilities encourage load shedding by targeting AC systems. In exchange for previously agreed on financial compensation, the utility will increase the thermostat set point or limit cycle runtime of a homeowner's AC system during critical times of the year [20]. Another way to encourage load shedding involves economic incentives, especially with time-based rates such as Time of Use, Critical Peak Pricing, Real Time pricing, in which the price of electricity is higher during peak hours. Utilities sometimes employ peak time rebates in which a user is paid to not use electricity during that time. Load shedding is encouraged to avoid extra load during both emergency situations and when projected demand outstrips production [21]. Clearly, peak power management is of major economic importance to T&D utilities.

3.2.4 Central AC Peak Power Example: Oklahoma Gas & Electric

The SmartHours program used by the utility Oklahoma Gas & Electric (OGE) illustrates how much utilities value removing peak demand. Air conditioning units turn on at similar times throughout a given region and therefore contribute to peak power load. Due to this effect, OGE provided incentives to their customers to move their demand to hours outside of peak times. By the simple distribution and free installation of a free programmable thermostat that alerts users to changes in upcoming energy pricing, a total of 2 kW peak demand per home was avoided since the program began [22]. In 2012, a total of 70 MW peak demand was removed from the 40,000 homes in the program [23]. Aside from the programmable thermostats, the SmartHours program experimented with smart metering, web portals for online management, and in-home displays to monitor energy consumption. OGE concluded that smart thermostats provide the most control over reduction in electricity consumption. OGE aims to defer investment in 170 MW of power plant infrastructure through such programs [24].

3.3 Significance

The results of this thesis identified the effects of the interactions between AC system size and thermostat schedule. In recent years, the method to curb residential energy has leaned toward managing energy demand at the point of consumption, such as with Demand Side Management (DSM). DSM is used by utilities to invest in reducing demand instead of investing in new infrastructure. As Palensky et al. explains, the main advantage of DSM is economic. Rather than build a new power plant or infrastructure to keep up with new demand, it is cheaper to lower the demand itself [25]. This idea is reflected in the motivation for the Oklahoma Gas & Electric free thermostat program. Palensky et al. states that the most important DSM type is Energy Efficiency, however the best option overall is the optimized combination of all categories as determined by economic incentives [25]. This research offers the beginning steps to fill this gap.

Finding ways to better control the consequences of power hungry equipment is more important than ever given the context of climate change, increases in renewable energy sources that destabilize the grid, and the trend in the reduction of coal mining [26], a common fuel for baseline energy production. Additionally, the International Energy Agency [27] has demonstrated that overall peak load will continue to increase over the next 35 years. Due to the challenges associated with generating and consuming peak power, efforts should be made to reduce and manage its generation and consumption. An improved understanding of the changes in greenhouse gas emissions from peak power reduction is important to the continued commitment to stricter emissions standards [28].

Many parties can be influenced through understanding the interrelationships between the economic, environmental and social factors of AC size and thermostat scheduling. The homeowner can make more informed decisions, positively impacting their wallet and environment. Socially focused policy makers and profit driven utility companies alike can evaluate tradeoffs to find incentives for consumers to reduce energy use, spare T&D losses, lower pollution emission rates, and save money.

4. Literature Review

This section explores existing literature surrounding the two main parameters to be analyzed, AC size and thermostat schedule. The human health, economic, and environmental aspects of using power from the central electrical grid is also discussed.

4.1 Air Conditioner Sizing

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 2013 Handbook of Fundamentals explains the major methods of AC sizing. The previously mentioned, Manual J of ACCA (8th edition) standard is widely used in the U.S. The calculations for the Manual J is based on experiments performed at the University of Illinois in the 1950s. Other methods include older versions of the ASHRAE Fundamentals Handbook between 1985 and 2001 that were the result of research performed in 1984. The research model included outdoor temperature swings, an important consideration for thermostat schedules. The final method noted in the Handbook is the Canada F280 method, which is based on the same research of the older ASHRAE versions [29].

As mentioned in Background Section 3, many AC systems are oversized. In a Florida case study, James et al. detail a few reasons why AC contractors choose systems larger than the standard. These reasons included reducing the number of customer complaints, not knowing if a customer will want cooler temperatures than the average customer, and avoiding a potentially difficult and time consuming Manual J calculation [30]. Burdick of the DOE found similar patterns [9]. Oversized units lead to an increase in annual energy consumption. For the hottest day of the year, houses with oversized systems showed 13% higher electricity consumption than homes with Manual J sized AC systems [30]. The authors explained that Manual J calculations depend greatly on the difference between the inside and outside temperatures with 75°F as the desired set point. However, they do not say that Manual J is designed to run for all but the average hottest 88 hours in a year. Even if the examined year is an average year, which it may have not been, it is possible that a Manual J sized system or one larger would likely run constantly on the hottest day of the year. As larger systems have a higher rated power than smaller systems, an oversized system would always use more electricity than a smaller unit assuming both run constantly. Research involving energy observations for longer than a day would provide wider insight to the sizing issue. This thesis research looked at energy use for an entire AC season, from early March through the end of November.

An HVAC sizing strategy guideline from the DOE [9] does not consider how the operational pattern may affect sizing. The guide explains how oversizing for the house can be detrimental for the system and the user. For example, the guide offers the analogy of a car's improved gas mileage on the highway to explain that the longer an AC system runs, the better. Short duty cycles stress AC equipment and decrease both efficiency and effectiveness. According to the guidelines, the most efficient and optimized mode for the AC equipment is to run for longer periods of time. Shorter cycles disallow for proper dehumidification because the unit is not running long enough for the coil to obtain the necessary temperature.

Electric utilities occasionally release recommendations for HVAC contractors to avoid this problem [31], but complaints of oversizing are still pervasive throughout discussions of AC sizing. Complaints are so common that the major influencers of energy efficiency in the U.S. have released their own literature both to raise awareness for consumers and to dissuade contractors from making poor calculations. Some of these institutions include the National Renewable Energy Lab (NREL) [9], ENERGY STAR [11], and ASHRAE [10].

4.2 Thermostat Schedules

Aside from AC size, the other major parameter analyzed in this study is the operational pattern of a programmable thermostat. According to the DOE, a seven to 10°F setback (or increase) of temperature for at least eight hours a day can save about 10% on home cooling and heating costs [32]. The following sections describe how thermostat usage is affected by a user's behavioral patterns and how the emerging field of smart technology is important to reducing residential energy consumption.

4.2.1 Human Behavior

In a discussion of how thermostats are scheduled, human behavior must be considered. Much of the energy consumption literature focuses on the variability of user behavior. A field study by Hargreaves et al. [33] explains the importance of the interactions among individuals in a household while the research of Pritoni et al. [12] explored the user's understanding of the technology. Another study suggests that a programmable thermostat can become inconsequential if the end-user were less concerned with both conservation and technology than other users [20]. Making energy consumption more visible may "signal pervasive and lasting reductions in domestic energy use," according to Burgess et al. [34]. The quoted authors also note that without pricing schemes, demand load control is not very useful. Finally, the smart thermostat is an attempt to encourage behavior that results in energy savings by aligning the user's behavior more closely with the thermostat schedule.

4.2.2 Smart Technologies

Smart technology is a new way to control thermostat schedules. Manufacturers promise larger energy reductions by more precise control over the runtime of an AC system. A smart home technology literature review points out that the technology is “not commercially exploited [which] makes it clear that there must be plenty of strategic, organizational and financial issues that require further attention” [27]. Exploring the issues that surround the smart thermostat more in-depth is important to motivate the customer stakeholder to see reduced energy usage across the grid. There are many papers that investigate how to extend the smart home with individual appliance use [35] or integrate the whole smart home system, such as in [38] and [39]. Studies often explore these network designs [38]–[40] while others form a schedule to avoid peak demand [41], although do not consider AC size. There is clearly a lack of research informing AC size and smart scheduling interactions.

4.3 Economic Costs

This thesis research considers costs associated with the generation of peak power. Peak load literature often explores user-response to peak demand pricing changes such as [20] and [42]. Using a simulation of 900 homes, Cole et al. found a new peak is not created when a community responds to changing electricity prices through load shifting [43]. They explored various strategies to reduce peak demand [43]. End-users respond to price changes as a motivator to reduce consumption during certain hours of the day. Enabling technologies, or technologies that help the consumer avoid peak prices such as a smart thermostat, have substantial opportunity to further enhance potential savings. For example, Faruqui et al. found that when enabling technologies respond to Critical Peak Pricing, whole house energy consumption dropped by 27-44% [44]. The potential savings from reducing energy use through timing is significant. As Newsham et al. describe it, the potential value to the customer is clear [20]. Reducing energy consumption 2-5% during peak hours can reduce the price charged to the customer by 50% or more. That reduction can become $3 billion in annual savings across the grid if the top 1% of peak consumption is reduced by only 5% [45]. Electric utilities are willing to pay for reduction in peak power through demand response programs, such as “Power Manager” from Duke Energy, which pays $32/year to customers to allow the utility to control their AC systems for a predetermined number of times. ConEdison promises commercial customers up to $18,000 per year for reducing energy usage during peak times in their demand response program [46]. According to electrical utility software company Opower, utilities spent $580 million in 2013 on demand response programming in an attempt to avoid peak loads, which is worth $94/year for one kilowatt of peak power on national average [47].

Jewell et al. investigated oversized AC and a demand response program in which the duty cycle was shortened to 20-minute intervals in Wichita. Various thermal integrities and two AC sizes were modeled [48]. Rhodes et al. examined energy audit data in Austin, Texas and showed that 31% of the 5,000 reviewed houses had oversized AC systems, leading to excess peak power load of 41 MW. Rhodes et al. then retrofitted the ACs to the correct size and implemented other efficiency improvements as suggested by the ENERGY STAR Home Performance program from the DOE and EPA. The authors quantified the amount of excess load that could be removed by comparing that year's data to historical peak power data. The resulting peak power demand savings were expressed as a benefit to the utility by equating the total potential load removal to the generating capacities of locally operating power plants [49]. The benefit of peak removal is also examined in this study, although the savings are in terms of dollars per year and consider an AC's peak power over a year, reflecting overall peak demand costs to the utility on a magnified scale.

Electrical utilities, especially the T&D companies, gain value from reduced peak. The U.S. average of T&D losses is 6% [50]. Load shifting from peak to non-peak would reduce T&D losses from centralized power generation because losses are proportional to the square of current flow [51]. Nourai et al. found economic benefits from reducing T&D loads during peak hours [51]. Using battery storage to shift load from peak to off-peak, they calculated a net present value of a few hundred dollars over several hours due to the reduction in T&D losses. The authors also found that reducing load across multiple sites realizes higher T&D efficiencies than if reduced in only a few places, further motivating T&D companies to promote peak load reduction.

4.4 Environmental and Social Costs

Erol-Kantarci et al. explored emissions reductions by moving appliance use to off peak times [52]. Peaker plants run on fossil fuels that generate greenhouse gas emissions. Consumers can lower these emissions by improving energy management. Therefore, the study shows that lower electricity consumption during peak hours not only lowers electricity bills, but also lowers carbon dioxide equivalent (CO_{2eq}) emissions of a household. However, in the study, air conditioning was not part of the simulated appliances.

One method to determine social costs associated with atmospheric pollution is called the Air Pollution Emission Experiments and Policy analysis (APEEP) model. Social costs can be measured in terms of impacts on human health. For example, by evaluating the amount of avoided particulate matter emitted smaller than 2.5 micrometers ($PM_{2.5}$) costs can be determined since $PM_{2.5}$ has been linked into increased mortality [53]. Other pollutants have similar health and other social effects. The APEEP model is "an integrated assessment model that links emissions of air pollution to exposures, physical effects, and monetary damages in the contiguous United States" [54]. Because the model can be used to represent marginal increases in pollutant exposures, APEEP was used in this research to compare the social impacts across different scenarios and to compare the economic costs against the social costs. The model uses county-specific data in the units of dollars per ton of the following individual pollutants: $PM_{2.5}$, SO_2 (Sulfur Dioxide), Volatile Organic Compounds (VOCs), NO_x (Nitrogen Oxides), and NH_3 (Ammonia). The damages included in the dollar value are the "adverse effects on human health, reduced yields of agricultural crops and timber, reductions in visibility, enhanced depreciation of man-made materials, and damages due to lost recreation services" [55]. APEEP has been used in various studies including one that considers electrical grid emissions [56].

According to the EPA, the smaller the particle size, the greater the potential damage. This is because smaller particles can not only enter a person's lungs, but also their bloodstream. Potential health effects include asthma, heart attacks, premature death and increased respiratory symptoms. Haze and acidification of local ecosystems is another effect of small particulate matter as well as material or aesthetic damage to surrounding environments [57]. Common health effects from VOC exposure range from fatigue and dizziness to more extreme effects such as damage to the liver, kidney and central nervous system, and are also suspected of causing cancer in humans [58]. At less than a dollar per year, VOCs and ammonia both have a minimal impact whereas sulfur dioxide and nitrogen oxides make up most of the social costs.

The total kilograms of three pollutants resulting from the electricity generation of each scenario are calculated in this thesis. The first of these is carbon dioxide. Carbon dioxide is released from the burning of fossil fuels and is globally monitored as a pollutant due to its known potential to retain heat in our atmosphere beyond levels that would otherwise naturally exist. This trait is called global warming potential. In the U.S., carbon emissions make up 80% of all such greenhouse gas (GHG) emissions due to human activity, such as generating electricity to run air conditioning. As of 2014, electricity generation is the largest source of carbon dioxide emission in the United States and accounts for 30% of all GHG emissions [59]. The second pollutant considered is sulfur dioxide. The EPA describes the health effects of atmospheric sulfur dioxide as a stressor or even a cause of respiratory diseases. It can also contribute to "increased hospital admission and premature death" by complicating existing heart disease [60]. Lastly are nitrogen oxides. Together nitric oxide (NO) and nitrogen dioxide (NO_2) are nitrogen oxides commonly referred to as (NO_x). Exposure to NO_2 can worsen asthma as well as inflame the airway. Ammonia reacts with NO_X in the atmosphere to create small particles that the human body is more susceptible to absorbing deep into the lungs [61].

5. Methodology

In this research, the DOE EnergyPlus software was used to simulate residential energy use for various combinations of AC sizes and thermostat schedules using two construction variations. Data from the 90 simulations and associated analyses show economic costs to the homeowners and utilities, energy use, pollution emissions and social costs for each AC-thermostat schedule combination. Together, the three types of analyses create a triple bottom line sustainability analysis.

5.1 Simulation & Data Collection

This section overviews the energy modeling software and details the major inputs examined during the research. The five major simulation inputs are shown in Table 1. The two inputs detailed here are the air conditioning system to be observed and the thermostat schedules they will be matched against.

Table 1: Energy model inputs

Constant	Location, weather data
Variable	AC system size, thermostat schedule, age of house construction

5.1.1 EnergyPlus

EnergyPlus is a building energy simulation software funded by the U.S. Department of Energy Building Technologies Office [62]. NREL's graphical user interface to EnergyPlus is BEopt version 2.6 and was used for the simulations. BEopt was used in residential energy usage studies [45], [52], and [53]**.** Sousa [65] recognizes that EnergyPlus is an "integrated solution" that contributes to precise space-temperature predictions, an important step to understanding and modeling accurate system sizing. EnergyPlus is used globally and accepted by researchers as a valid tool to analyze building energy consumption and potential alternatives to promote energy reduction. Heat transfers are determined using algorithms that consider building physics. EnergyPlus has been updated twice a year since debuting in 2001 [66]. The Energy Plus software is categorized as an engineering method bottom-up technique. BEopt's many inputs, such as climate data, temperatures, and AC system characteristics makes this technique a strong choice to model new technologies [67].

5.1.2 AC system

EnergyPlus allows users to model using time step simulations for HVAC systems. This detail was necessary for this research and results were displayed in singular kilowatt-hours for the entire 8,760 hours of a year. EnergyPlus comes preloaded with HVAC systems that can be altered by individual components. Creating a new HVAC system is also possible using an independent data set for efficiency ratings, number of speeds, capacity ratio, condenser type, fan speed ratio, rated and installed supply fan power, etc.

All modeled AC capacities were Seasonal Energy Efficiency Ratio (SEER) 13 systems. SEER is the cooling output per time unit divided by the amount of energy consumed by the system per time unit.

The modeled AC capacities ranged from the BEopt Manual J calculation for the home described in the next section, to larger systems often chosen by contractors as well as smaller capacities for comparison. The calculated Manual J value in EnergyPlus does not round to the nearest half-ton when performing its analyses. Therefore, the resulting Manual J sizes are in between commercially available sizes. Five sizes total were modeled for each thermostat schedule. The sizes included the Manual J size itself and the four choices available to an AC installation contractor: the two sizes larger than and the two sizes below the Manual J value, in increments of commercially available 0.5-tons. If a residence requires beyond a 5.0-ton capacity, common practice is to have two smaller sized units. In this study, the older construction type home, described in Section 5.2, had a Manual J value of 4.9-tons. For consistency, 5.0- and 5.5-ton units were used for the two sizes beyond the Manual J 4.9-ton value.

5.1.3 Thermostat Schedule

The cooling schedules used in the simulations are detailed in Table 2. The three starting temperatures for these schedules were chosen based on industry standards and DOE recommendations. The 2013 ASHRAE Fundamentals Handbook suggests indoor temperature designs use 75.2°F as the dry bulb temperature with a maximum 50-65% relative humidity. The ASHRAE Standard 55-2013, Thermal Environmental Conditions for Human Occupancy, suggests a comfortable thermal range is between approximately 67°F and 82°F. ACCA's Manual J uses 75°F as the desired indoor temperature for their design calculations. ENERGY STAR suggests all cooling set points are 78°F or more during occupancy [32]. To account for variance of human comfort, data from the 2009 US EIA Residential Energy Consumption Survey (RECS) Table HC7.11 were used to choose three starting set point temperatures of 70°F, 74°F and 78°F.

Government-recommended setbacks informed the three schedule types that use the three starting set points. The thermostat schedule would not need to change if there were an occupant during the day. The DOE suggests using programmable thermostats if the house will be unoccupied for at least four hours [32]. Therefore, the simulations are only relevant to those not usually home in the daytime during the workweek. However, the constant thermostat schedule could be viewed as the schedule for a home that is constantly occupied. Setbacks were modeled for ten hours on weekdays between 8am and 6pm, with constant temperature setting on the weekends. Programmable thermostats in BEopt are hardcoded to begin cooling an hour before the desired temperature is to be obtained. The amount of setback was determined by the ENERGY STAR suggestion of adding at least 7°F when unoccupied. Constant schedules, or schedules maintaining one set point temperature, were included at each starting set point temperature. An off schedule is a setback where the user turns their system off while away, allowing the temperature to rise without restriction depending on the envelope of the home and the outdoor temperature. A summary of these schedules is found in Table 2. A total of three schedule types (Constant, Plus Seven, Off) were modeled for each of the three starting temperatures (70°F, 74°F and 78°F). Those nine scheduling scenarios were modeled for each AC capacity described in the previous section, resulting in 45 combinations for a single home, or 90 scenarios total for the two construction types.

Table 2: Summary of simulated thermostat schedules with three schedule types and three starting set point temperatures. These nine schedules were used for each AC capacity and both new and old home construction type over the weekday from 1 March – 30 November.

	Starting Set Point Temperature (set point/setback)		
Schedule Type (setback period)	**70°F**	**74°F**	**78°F**
"Constant" (NA)	70°F/70°F	74°F/74°F	78°F/78°F
"Plus Seven" (8am-6pm)	70°F/77°F	74°F/81°F	78°F/85°F
"Off" (8am-6pm)	70°F/Off	74°F/Off	78°F/Off

5.2 Location, House Design and Construction

Phoenix, Arizona was chosen as the location for this study for the following reasons. First, Phoenix has a warm and dry climate, which simplifies the scope of the study by avoiding issue with humidity. NREL's Typical Meteorological Year (TMY) 3 climate data is preloaded in BEopt and is depicted for the Phoenix region in Figure 6. Phoenix is included in the projected "intense growth" of both electricity demand and population in the American southwest into 2025 [69]. Similarly, Phoenix has a substantial population density and saturation of central AC use. For these reasons, Phoenix Arizona was the location examined in this study. Phoenix is part of the WECC Southwest division as designated by the US Energy Information Administration (EIA).

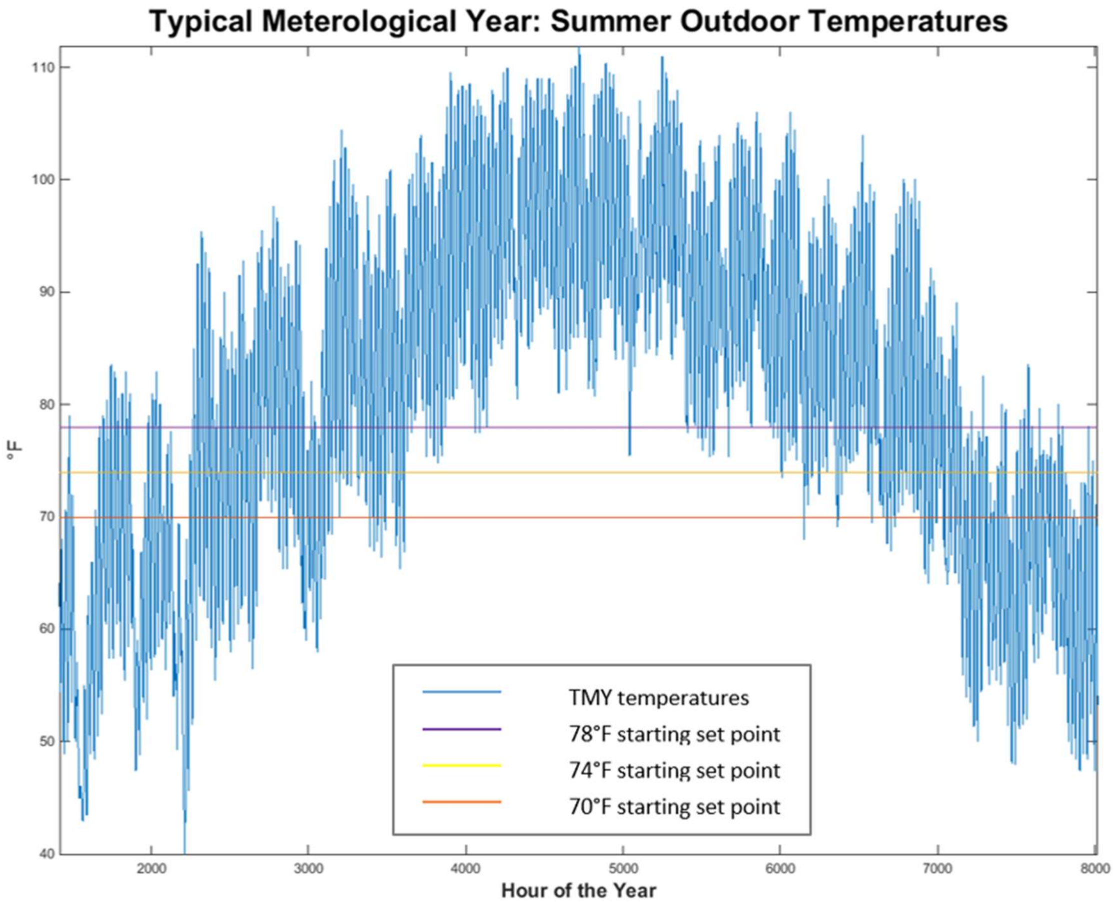

Figure 6: NREL's TMY outdoor temperatures used in the simulation against the three set point starting temperatures

The city of Phoenix's Planning and Development Department tends to adopt national and international standards and not create other measures [60]. Therefore, the house design specification was based on local average residential units and DOE recommended values. Two overall cases will be considered to represent both new construction since 2010 and older construction that make up houses from 1980 – 2009, about 1.2 million homes in Arizona (Arizona - Table HC2.11 Structural and Geographic Characteristics of Homes in West Region, Divisions, and States, 2009) [70]. For houses built since 2010, Building America's B10 benchmark design, which includes 2009 IECC housing codes, was used to inform new construction. The necessary R-values for insulation and other characteristics of the B10 Benchmark is an option within the BEopt software for new construction and therefore straightforward to model.

The case that represents the existing older homes in the Phoenix region was defined using a base case scenario from Walsh et al. [71]. Table 3 defines the difference between the Walsh et al. case and the older home construction type modeled in this research. There were options not included in the Walsh et al. scenario that needed to be defined within BEopt to represent an older home. BEopt's retrofit options informed those other characteristics as follows. Air leakage of 10 ACH50, or ten air changes per hour at a pressure difference of 50 Pascals, is considered "typical" by research cited within BEopt. Duct leakage is a significant contributor to the building envelope. The standard 15% leakage with R-4 insulation was used in this research. The refrigerator type was chosen to have the freezer on top and an Efficiency Factor of 15.9, a value between 17.6 from the B10 Case and closer to the least efficient retrofit option of 14.1. For both cases, the DOE Housing Simulations Protocols set the standard operating conditions of the house such as refrigeration, lighting, manual ventilation (such as opening windows).

Table 3: Older Home BEopt specifications based on the modeled home from Walsh et al.

Construction Type	Base Case (Walsh et al.)	BEopt Option
Building Envelope/Wall	2X4 R-13	Walls: Wood Stud Option 6: 2X4 R-13 Fiberglass Batting
Building Envelope/ Ceiling	R-30 Blown-in	Ceilings/Roofs: Unfinished Attic Option 23: Ceiling R-30 Open Cell Spray Foam, Vented
Building Envelope/ Attic	No Radiant Barrier	Radiant Barrier Option 1: None
Building Envelope/Ceiling	No slab-edge insulation	Foundation/Floors: Slab Option 1: Uninsulated
Fenestration	Clear, double pane window with aluminum frame	Windows & Doors: Windows Option 1: Clear, double, metal, air
Fenestration	No exterior shade screens	N/A
Fenestration	Wood Doors	Doors Option 1: Wood
HVAC System	SEER 10	Central Air Conditioner: Option 2: SEER 13
HVAC System	R-4 duct insulation with taped joints	Ducts Option 11: 15% Leakage, R-4

The size of the modeled house was 2,100 square feet. US census data shows that of new construction in 2010 in the western region, most homes were in the 1,800-2,400 square foot range, with an average of 2,100 square feet [72]. Two-car garages have been common in the western US since the 1970s and therefore the generic standard sized 22' X 22' garage was included in the model [72]. All of the preset BEopt 2.6 settings for the building structure were kept unless otherwise discussed.

5.3 Economic Analyses

The analyses performed in the upcoming sections were calculated using the resulting simulation data. Economic analyses were performed to show influences on stakeholders. This analysis included the basic cost of running the system in the home, the net present cost, costs of energy generation by the power generator utility, and peak load costs to the T&D utility.

5.3.1 Electricity Cost To The Consumer

The price of electricity used for this study was collected from Open Energy Information [73], an online open database populated by data from the Energy Information Agency (EIA) and was the average of the total revenue and sales of the T&D utility in the area. The EIA average rate for residential customers in the 85041 zip code for Phoenix, AZ is 10.9 cents/kWh [74]. The pricing will remain constant throughout the entire year period of analysis to allow for comparisons with other schemes.

5.3.2 Net Present Cost

The cost of owning and using the AC system to the homeowner was determined using the Net Present Cost equation for a uniform series, since there are fixed annual payments for a fixed number of periods. In Equation 1, I_o was the initial investment, *c* was the annual cost of purchasing electricity, N was the average lifespan of the unit as given by BEopt as 16 years, and i was the discount rate set to 5%.

$$Net\ Present\ Cost = I_o + \frac{c(1+i)^N - 1}{i(1+i)^N} \qquad (1)$$

Where I_o was both the initial investment of the $411 installation cost as provided by BEopt and the cost of the AC system. The actual cost of the SEER 13 system does not change by capacity within BEopt. Therefore, three major AC brands (Ameristar, Goodman, and Guardian) were used to find an average price for each tonnage, while cost for 3.6-, 4.5-, and 5.5-ton were interpolated from that same data due to lack of market availability [75] as seen in Table 4. The increasing trend in price as capacity increases is seen in Figure 7. The annual cost of purchasing electricity, c, was described in the previous Section 5.3.1. Discount rate i was set as 5%. The average lifespan of the unit, N was also provided by BEopt as 16 years. The resulting Net Present Cost (NPC) was described using US dollars from the year 2016.

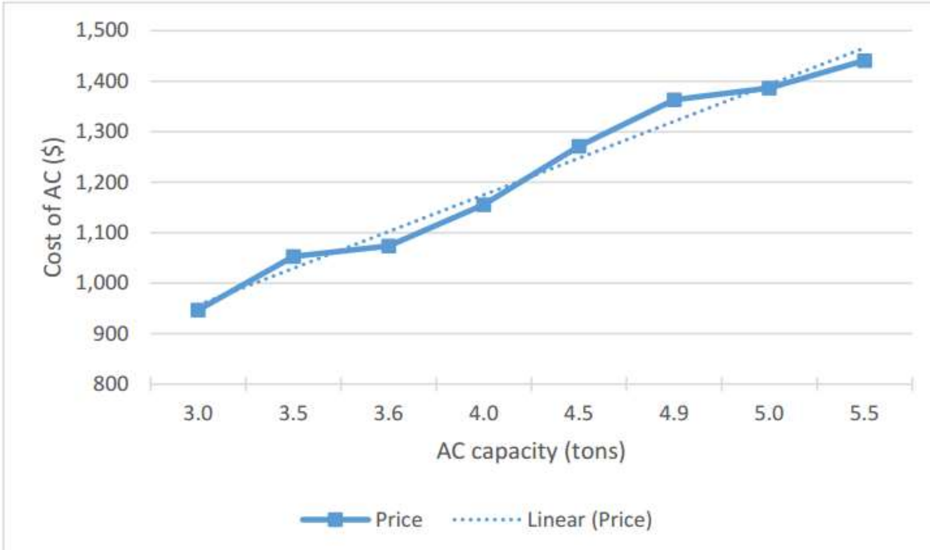

Figure 7: Capital investment cost of AC systems used to calculate economic analysis.

Table 4: Purchase prices used in this study. Average prices for commercially available AC systems in sizes 3.0-, 3.5-, 4.0-, 5.0-ton and interpolated prices for non-commercially available 3.6-, 4.9-, 5.5-ton AC systems.

3.0-ton	3.5-ton	3.6-ton	4.0-ton	4.5-ton	4.9-ton	5.0-ton	5.5-ton
$946.70	$1,052.96	$1,073.50	$1,155.67	$1,270.99	$1,363.24	$1,386.30	$1,441.14

5.3.3 Peak Load Costs

The costs of meeting peak demand include the maintenance of generation, transmission, and distribution resources that are rarely (or perhaps never) used. These "costs" may better be thought of as unrealized savings that occur if peak demand can be reduced through other means, such as home energy efficiency initiatives. An average monthly demand charge for residential customers in the Arizona Public Service Electric Company of $11.40/kW is used to calculate the annual peak load cost as seen in Equation (2) [76].

$$P = \sum_{m=March}^{November} P_m * 11.40 \qquad (2)$$

This charge was used to represent the benefit of reduced demand to the utility. This method was compared to a similar calculation using payments within capacity markets that also track cost impacts of peak loads and yielded similar results. The major difference is that capacity markets represent the entire Independent Operating System (ISO), whereas demand charges represent the individual electrical utility.

5.3.4 Cost of Generation

The generation cost (GC) metric was included because the consumer demand of energy influences the cost of generation, which can vary drastically with time. If demand is shifted to periods of lower generation cost, both consumers and utilities benefit. The hourly wholesale energy pricing of the Arizona-New Mexico region was used to determine an annual electricity production cost as specified in Equation (3) where kwh_t is the electricity consumed during hour t of the simulation, and GC_t is the generation cost at time t. This generation cost was calculated using the data set provided by Hittinger et al., as collected from the southeastern border of the California Independent Systems Operator [77]. This cost was calculated for each of the 90 combinations. The results provide insight into potential subsidies to decrease generation costs.

$$GC = \sum_t kwh_t * GC_t \qquad (3)$$

5.4 Environmental Analysis

Two environmental analyses were performed. The first calculated the resulting pollutants emitted by using electricity from the grid. The other analysis determined the residential in-home impact of the amount of time an AC system did not reach the desired set point.

5.4.1 Marginal Emissions Factors

Avoided pollution due to electricity generation will be measured by using standardized marginal emissions factors (MEFs) calculated in [78]. As previously explained, as demand increases more generators turn on to feed the grid to meet the demand. An MEF describes how much NO_X, SO_2, CO_2 emissions are released per unit of power as categorized by the latest generator added to the grid. For example, if the number of kWh avoided can be aggregated per each hour, then the specific MEF that matches the demand that hour can be applied. This method was used in a study showing that battery storage generally increases emissions [70]. Each state generates their electricity through varying methods at different magnitudes, which in turn affects the amount of generated emissions. The energy mix of New York state is based on mostly nuclear and hydroelectric dams, which generate fewer carbon emissions than a more fossil fuel heavy mix. In 2013 as a result of energy generation, New York emitted 8.1 metric tons of CO_2 per person, whereas Arizona had almost double that at 14.1 metric tons of CO_2 per person [79]. As of August 2015, Arizona had a mix of mostly natural gas-fired, coal-fired, and nuclear electricity generation. A less significant 1,000 GWh out of the total 12,544 GWh production was from hydroelectric and other renewables [80]. Another example of how pollutants differ across states is in the carbon intensity of energy production that varies by state. In 2013, coal heavy West Virginia had an energy intensity of 79.9 kg CO_2 per million Btu whereas New York state has a much lower carbon intensity of only 44.9 kg CO_2 per million Btu [79].

5.4.2 Unmet Loads

A metric describing unmet loads is detailed in Equation (4). In Equation (4), UH_t captures the hours when the cooling load is not met, specifically UH_t is equal to 1 for any time period when the indoor temperature I is greater than the desired set point a (S) with an industry standard one degree tolerance [81]. The magnitude of the unmet loads at time t, UH_t, is the total observed temperature difference between the desired indoor temperature and the set point at any period t. Finally, the total unmet cooling load (UCL) is calculated in DegHrs, and is the sum of all UH_t in hours across the simulation time frame. BEopt is hardcoded to only consider AC cooling between March 1st and November 30th, all 6,600 hours. Therefore, all mention of annual metrics is defined by only these nine months of AC operation.

$$UH_t = \begin{cases} 1 & if\ I > S + 1 \\ 0 & otherwise \end{cases}$$
$$|UH_t| = \begin{cases} I - (S + 1) & if\ \ UH_t = 1 \\ 0 & otherwise \end{cases} \qquad (4)$$
$$UCL = \sum_{t}^{6{,}600\ hrs} |UH_t|$$

5.5 Social Cost Analysis

This section first explains the APEEP model that translates pollution emissions to a price associated with its impacts on humans interacting with their environment. Secondly, the inputs used to determine optimization of the AC size and schedule combinations across society are detailed.

5.5.1 The APEEP Model

In order to use the correct energy mix for Phoenix and county level information, the Federal Information Processing Standard (FIPS) code for Phoenix (04-013), provided by the US Census Bureau [82], was cross-referenced with the FIPS code entries in the APEEP data available on the website of the creator of APEEP, Nick Muller [54]. The most recently available marginal prices for 2008 for the five pollutants were used and were in dollars of social cost from the year 2000 per short ton for each pollutant. These prices were multiplied by the amount of each pollutant generated in each AC combination scenario. As only state-wide rates were available, the rates for pollution emissions were calculated by finding the total emissions in tons of each pollutant due to fuel combustion for electricity generation in Arizona in 2008 from the National Emissions Inventory [83] and the total electricity generated in 2008 in Arizona from the EIA in 2008. The data was found in the electricity Data Browser under net generation for electric utility only [84].

5.5.2 Net Benefit for Society

Four sets of results were added to determine the net benefit to society, as seen in Equation 5.

$$Total\ Societal\ Cost\ (TSC) = EMC + GC + P + Io \qquad (5)$$

Total Societal Cost is defined as the summation of the initial investment of the AC system (installation and purchase cost) to the homeowner (I_o), the social cost of the marginal emissions results for carbon dioxide and the five APEEP social costs results (EMC), and finally, the costs of both peak load (P) and generation to the utility (GC). Generation cost was included because as homeowners determine the demand of energy, that demand influences the cost of generation. If the cost of generation decreases, so will the price of electricity and both stakeholders benefit. A similar effect occurs for peak load costs. Environmental emissions can affect the entire local population and the initial costs to the homeowner to have AC equipment matter because the sizes of the systems affect energy demand, which again can put more costs back onto both the homeowner and utilities. The costs for all 90 scenarios were evaluated and the lowest cost scenario is considered the best one for society.

For consistency, the initial net present cost was annualized using the capital recovery factor, where A is annualized cost and P is the initial investment, n is the 16-year lifespan and i was 0.05% as seen in Equation 6.

$$A = P\left(\frac{i(1+i)^n}{(1+i)^n - 1}\right) \qquad (6)$$

In order to monetize the carbon dioxide results, the EPA's social cost of carbon for the latest year of 2015 was \$11 per metric ton at a 5% discount rate in year 2007 dollars [85]. The Consumer Price Index (CPI) was used so that the results would be in dollars for the year 2016. To change the APEEP prices from year 2000 and social cost of carbon from 2007 dollars to 2016 dollars, the following CPIs from the Bureau of Labor Statistics were used in Equation 7: 172.2 (Year 2000), 201.6 (Year 2007), and the 2016 CPI was the average of the four months available, 237.855 [86].

$$2000\ Price\ \left(\frac{2016\ CP}{2000\ CP}\right) = 2016\ Price \qquad (7)$$

For example, the year 2000 price of Sulfur Dioxide according to the APEEP model is \$21,777 per short ton. Therefore, the 2016 price would be about \$30,000 per short ton or \$15 per pound.

$$\$21{,}777\left(\frac{237.855}{172.2}\right) = \$30{,}079$$

6. Results

The Manual J calculated load for the newer construction, the 2010 Benchmark America home, was 3.6-tons. For the older home with different construction parameters, it was 4.9-tons. The outcomes of each output metric described in the methodology for all ninety possible combinations of older or newer home, AC capacity, thermostat set point, and schedule type are shown in this section. The results are organized by the entity directly impacted by each result beginning with the homeowner, then the power generators and T&D utilities, and finally society.

6.1 Outcomes for Homeowners

This section contains results that are relevant to the homeowner, such as direct energy cost and consumption. Homeowner comfort is accounted for in terms of when the system could not perform to the temperature set points imposed by the homeowner. Finally, the net present cost is presented.

6.1.1 Direct Energy Consumption & Cost

In Figure 8, the results, like most of the graphs to follow in this section, are grouped by the schedule type and thermostat set point in ascending order. Each simulated combination had a different amount of power consumption for the one-year scenario. Less power was consumed as the set point increased as well as for the number of hours the indoor temperature was permitted to increase.

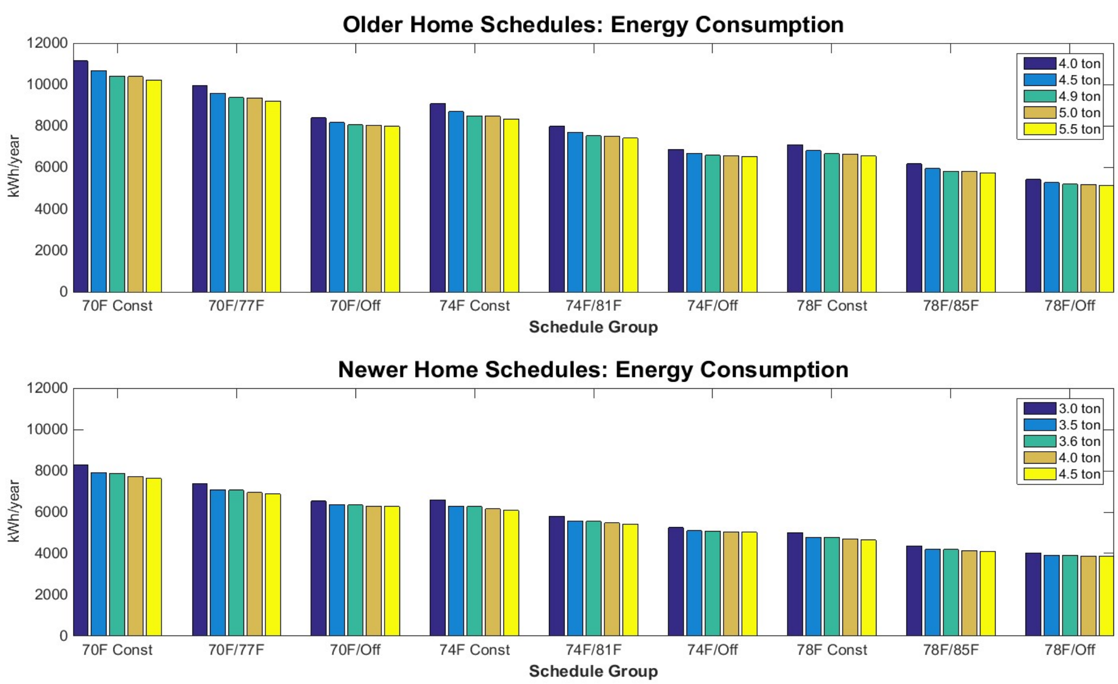

Figure 8: Energy consumption of each scenario

The direct cost of consumption seen in Figure 9 is directly proportional to electricity consumption in Figure 8. This direct relationship is because the energy consumption was multiplied by a constant price of 10.9 cents/kWh. Costs for the older home ranged from 24% to 28% higher than that of the newer home.

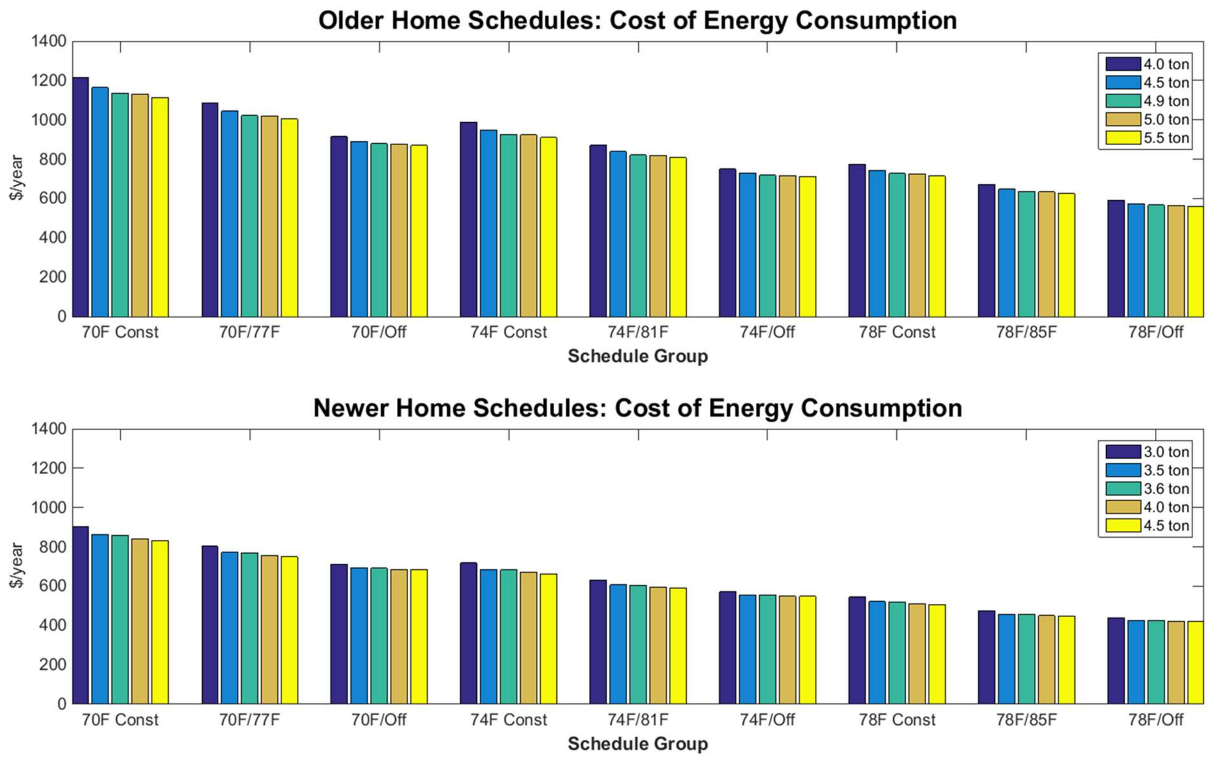

Figure 9: Direct cost of energy consumption to homeowner for one year.

6.1.2 Unmet Loads

The upper portion of Figure 10 and Figure 11 reveal the number of hours in the simulated year for which the actual indoor temperature does not meet the set point plus one degree Fahrenheit. The lower portion of Figure 10 and Figure 11 show the magnitude of that unmet load by incorporating by how many degrees it was away from the set point with an allowance of one degree above the set point. Clearly, the schedule is more influential than the AC capacity and larger capacities have fewer unmet loads. This trend is especially noticeable in how the smallest system for the older home with the 70°F/77°F schedule has the largest unmet degree-hours for that schedule group, but is still about 50% less than for the largest system in the 70°F/Off group.

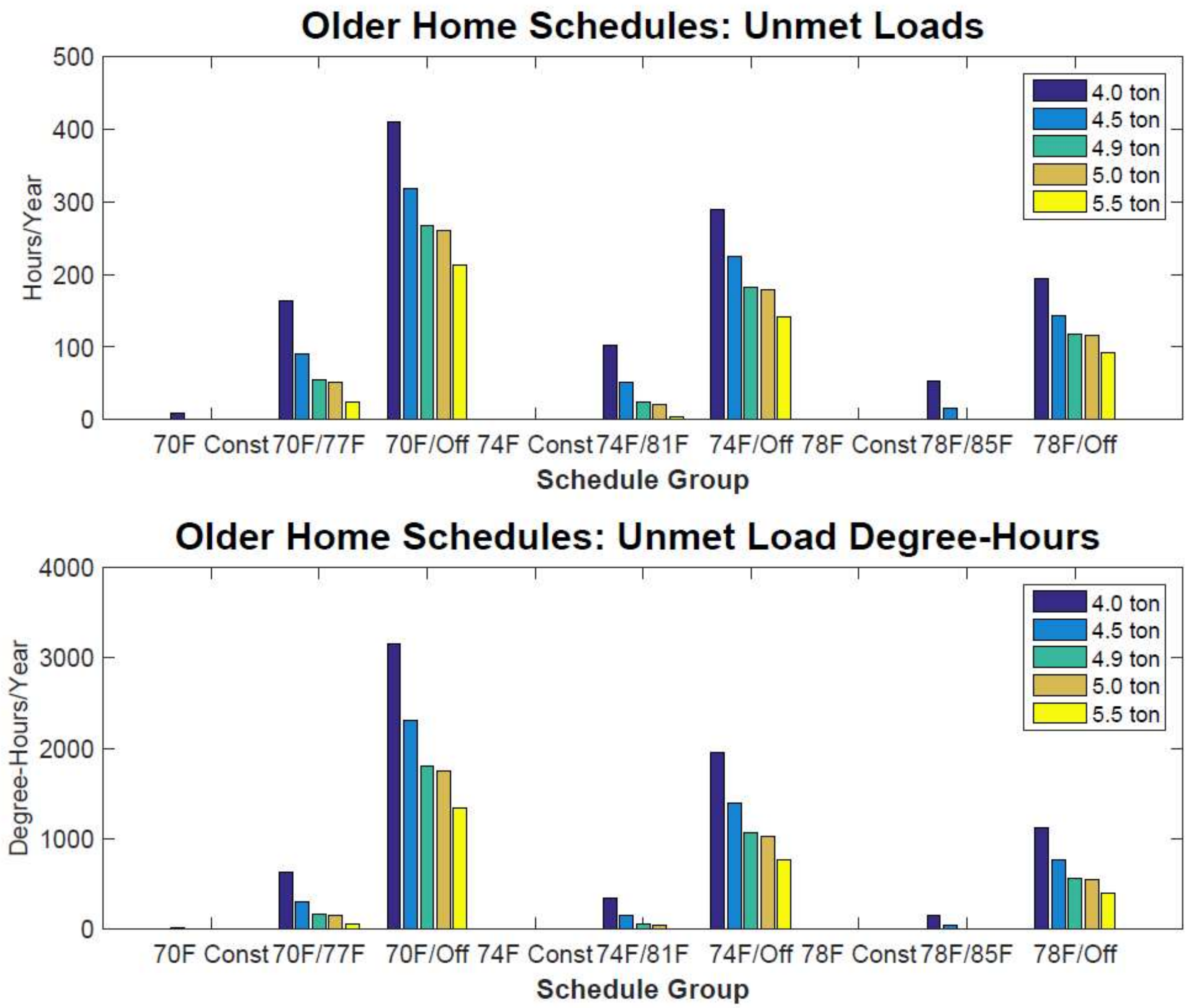

Figure 10: Hours and magnitude of unmet load in the older home

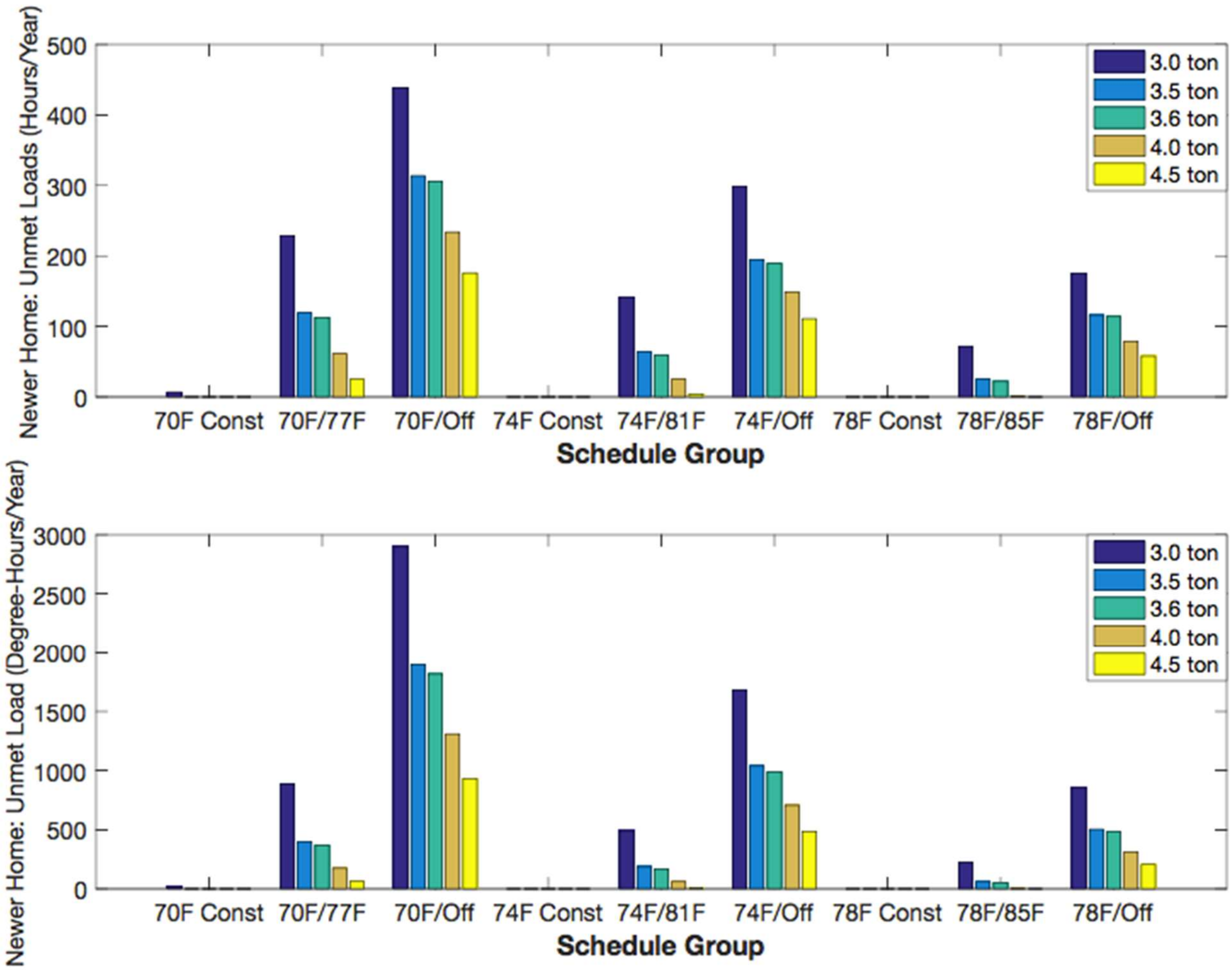

Figure 11: Hours and magnitude of unmet load in the newer home

6.1.3 Net Present Cost

Figure 12 shows the net present cost to the homeowner over the 16-year lifespan of the system, including the fixed installation cost of $411 and the variable costs of power consumption and AC system purchase price that changes based on the system's capacity. The two home construction types followed similar trends by schedule group, although the net present costs were typically larger for the older homes.

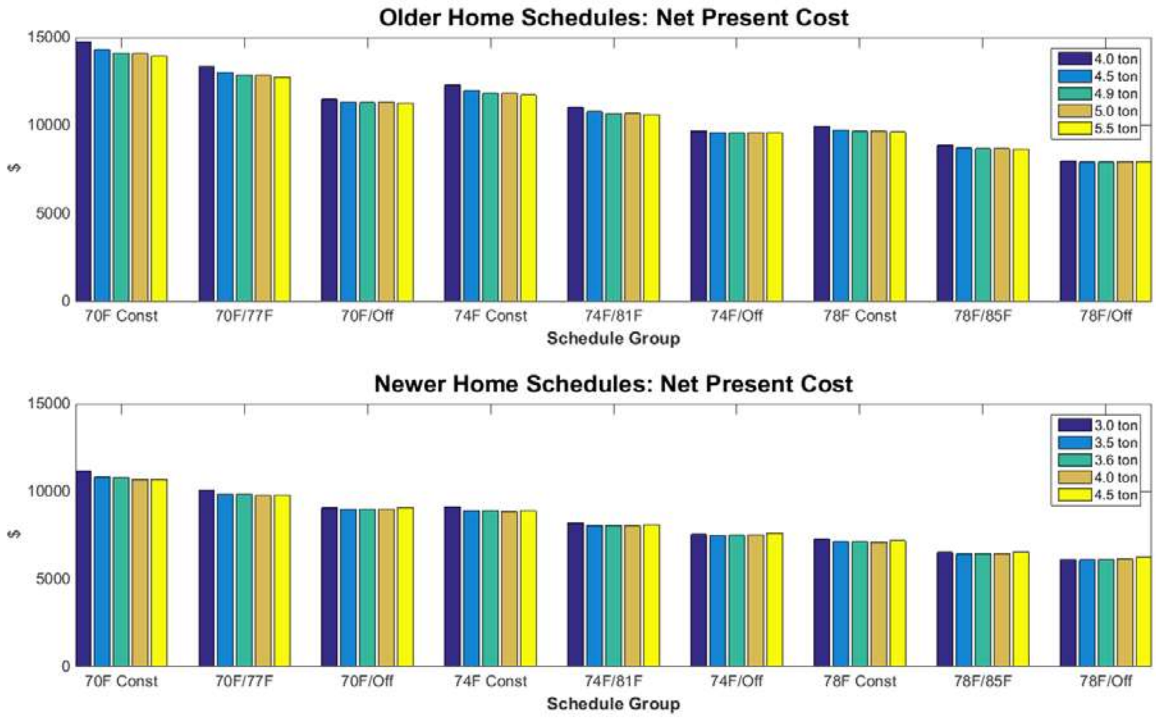

Figure 12: Net present cost to the homeowner

6.2 Outcomes for the Utilities

Two factors that are important to the utilities are economic. First is the cost to generate power given the time of day. The second is the cost of peak power through demand charges. Both sets of results are presented in this section.

6.2.1 Generation Cost

Figure 13 shows that overall, for a given schedule group, changing between different AC capacities only changes the generation cost by less than $40 for new homes and by less than $50 for old homes annually. Across the 1.2 million older homes in the region, a maximum annual savings is $60 million. The constant schedules of each temperature group are the costliest to generate. These results were generated using wholesale prices.

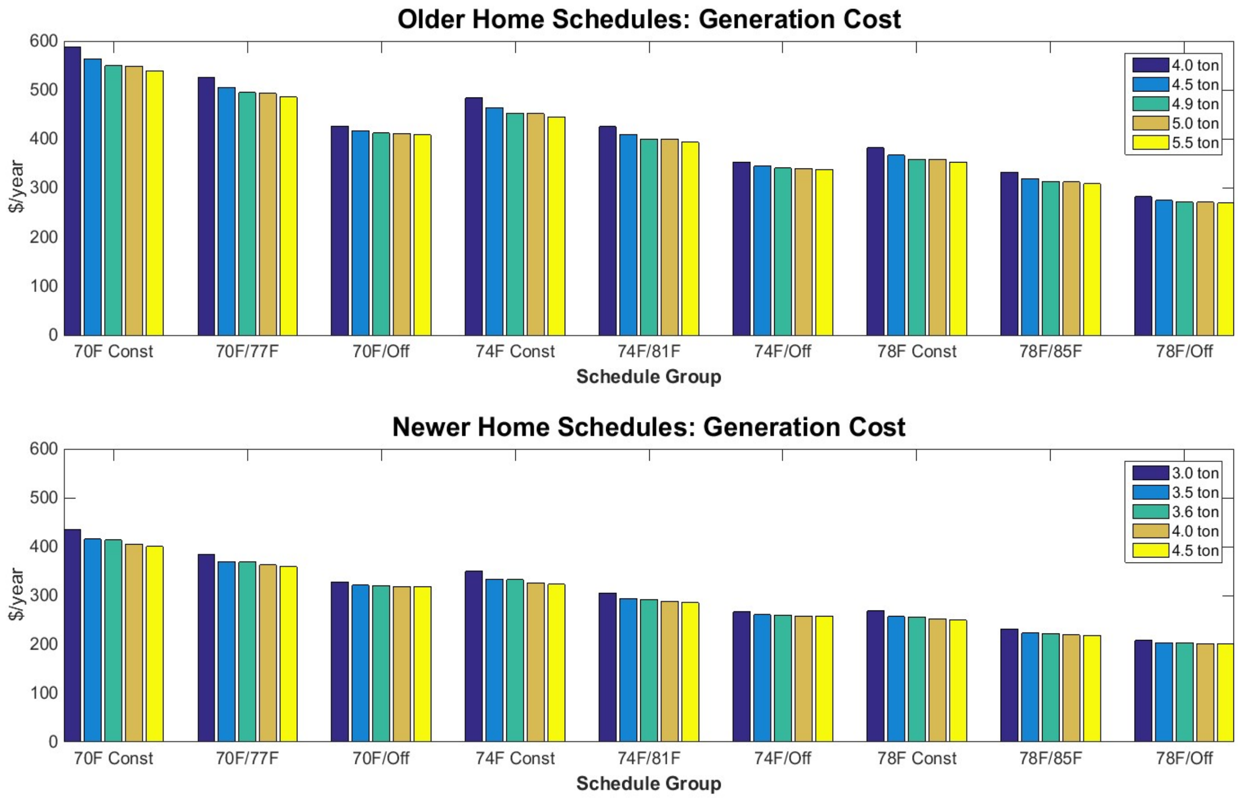

Figure 13: Cost to local utility to generate power for one year.

6.2.2 Peak Loads

The monthly peak power consumption and cost is shown in Table 5 and Table 6, including the monthly peak range across all thermostat schedules. The "cost of peak power" is the amount of monthly peak power multiplied by the $11.40/peak kW/month demand charge. Each scenario had its own monthly peak power consumption and peak power for each billing month was summed to result in the annual peak load costs. The range of the annual cost are organized by capacity. As seen with the average cumulative peak power across the 45 temperature setting scenarios in the older home, annual peak power consumption increases overall with capacity, as one might expect due to higher rated power. Trends for both construction types are easily visible and are directly proportional to the peak kilowatt patterns.

Table 5: Peak load costs for the old home.

AC Capacity (tons)	Range of monthly peak power across scenarios (kW)	Average monthly peak power (kW)	Average monthly peak cost ($)
4.0	3.44 - 4.85	3.26	37.16
4.5	3.28 – 5.15	3.36	38.30
4.9 “Manual J”	3.19 – 5.48	3.44	39.22
5.0	3.12 – 5.53	3.45	39.33
5.5	3.11 – 5.91	3.53	40.24

Table 6: Peak load costs for the new home.

AC Capacity (tons)	Range of monthly peak power across scenarios (kW)	Average monthly peak power (kW)	Average monthly peak cost ($)
3.0	2.45 – 3.55	2.37	27.02
3.5	2.32 – 3.87	2.50	28.50
3.6 (Manual J)	2.31 – 3.92	2.51	28.61
4.0	2.24 – 4.26	2.60	29.64
4.5	2.21 – 4.63	2.69	30.67

6.3 Emissions and Social Outcomes

This section first contains results derived from computing the emissions of each scenario using the marginal emissions factors as well as social impact costs using the APEEP model. Second, the Total Societal Cost are presented.

6.3.1 Emissions

The APEEP results demonstrate the social impact in dollars of pollutants that resulted from electrical generation to provide power to each of the AC systems. The social impacts consider health effects, effects on manmade materials, forestry, agriculture, visibility and recreation [55]. As all trends were very similar across all pollutants, a description of the effects of the pollutant is offered. Results for both MEFs and APEEP are organized jointly by pollutant. The order of presentation is as follows: carbon dioxide emissions (Figure 17), particulate matter less than 2.5 microns (Figure 18), sulfur dioxide (Figure 19 and Figure 20), nitrogen oxides (Figure 21 and Figure 22), ammonia (Figure 23), and volatile organic compounds (Figure 24). All costs are displayed in 2016 dollars.

Across all thermostat schedules, smaller AC systems produced more pollutant or social impact cost due to a pollutant. This was due to the increased total electricity of smaller systems, because they are less efficient at removing a given unit of heat over a period than larger systems.

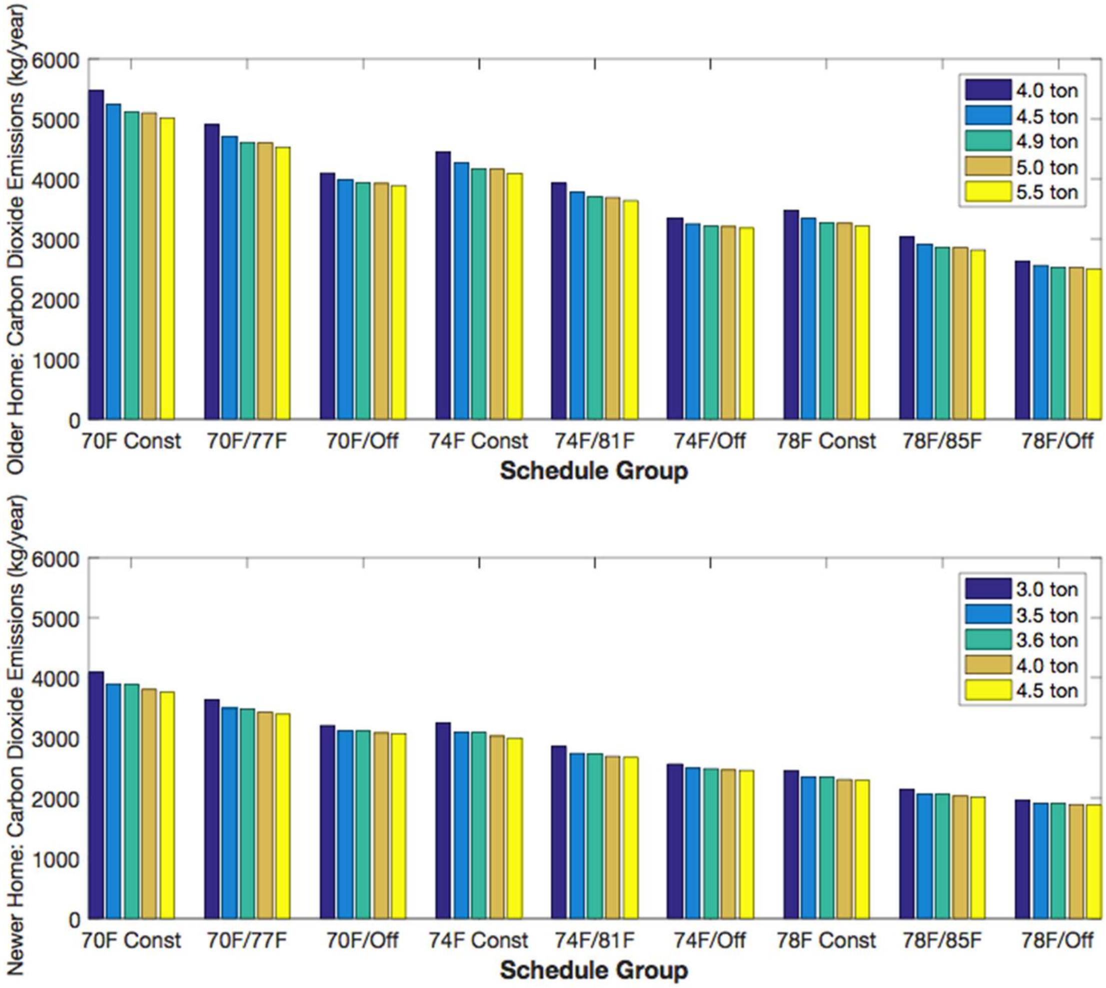

Figure 14: Marginal carbon dioxide emissions for all scenarios

Carbon dioxide emissions, as seen across all environmental and social results, are larger for the older home than the newer home.

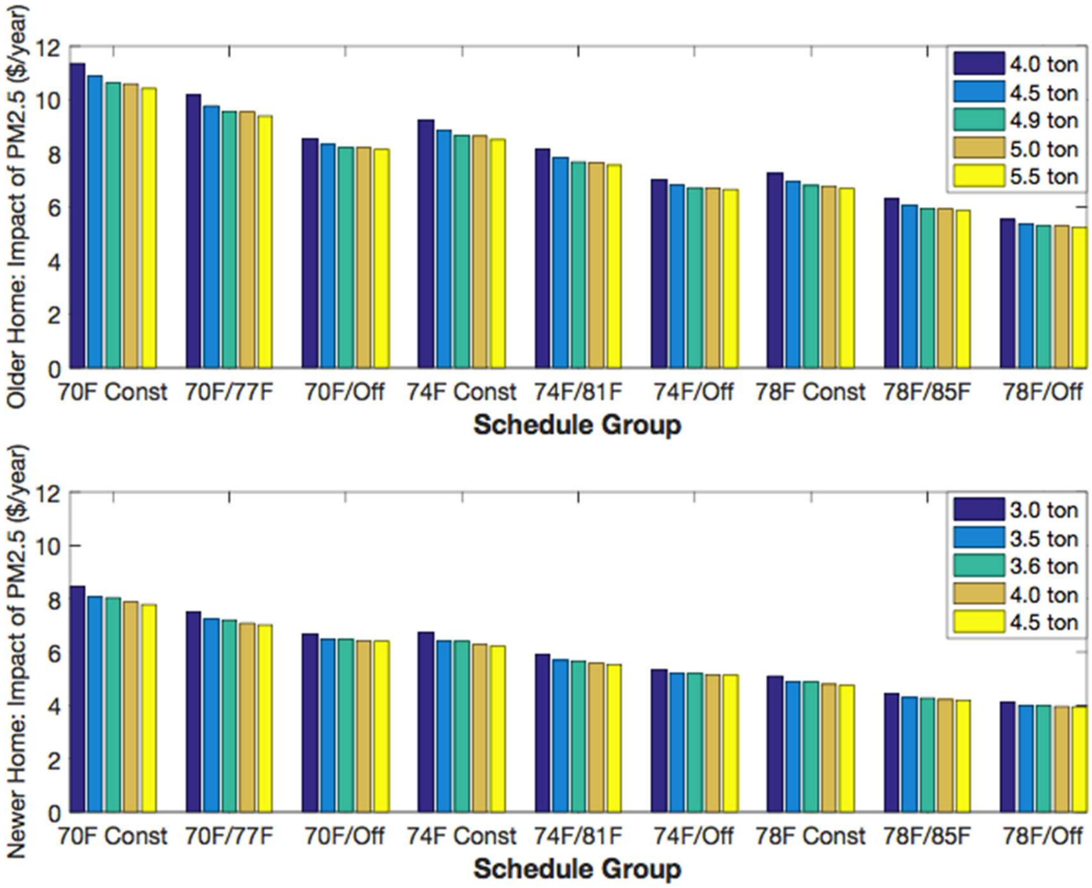

Figure 15: Dollar value impacts from particulate matter emissions of 2.5 microns or less

Social impact costs for particulate matter are less than $15/year per home. The minimum social cost is $7.2 million of damages in this region of 1.2 million older homes.

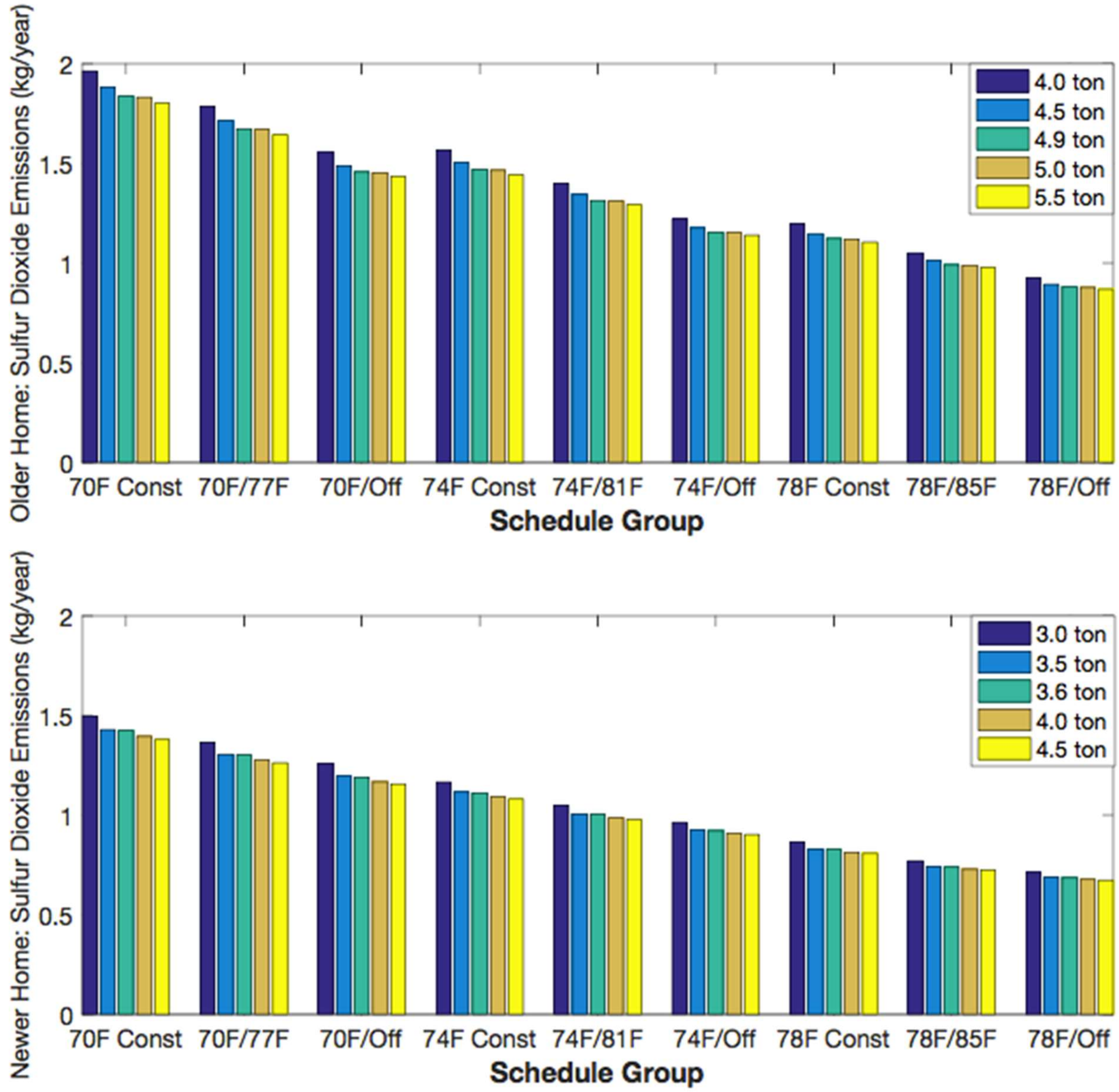

Figure 16: Marginal emissions results for sulfur dioxide

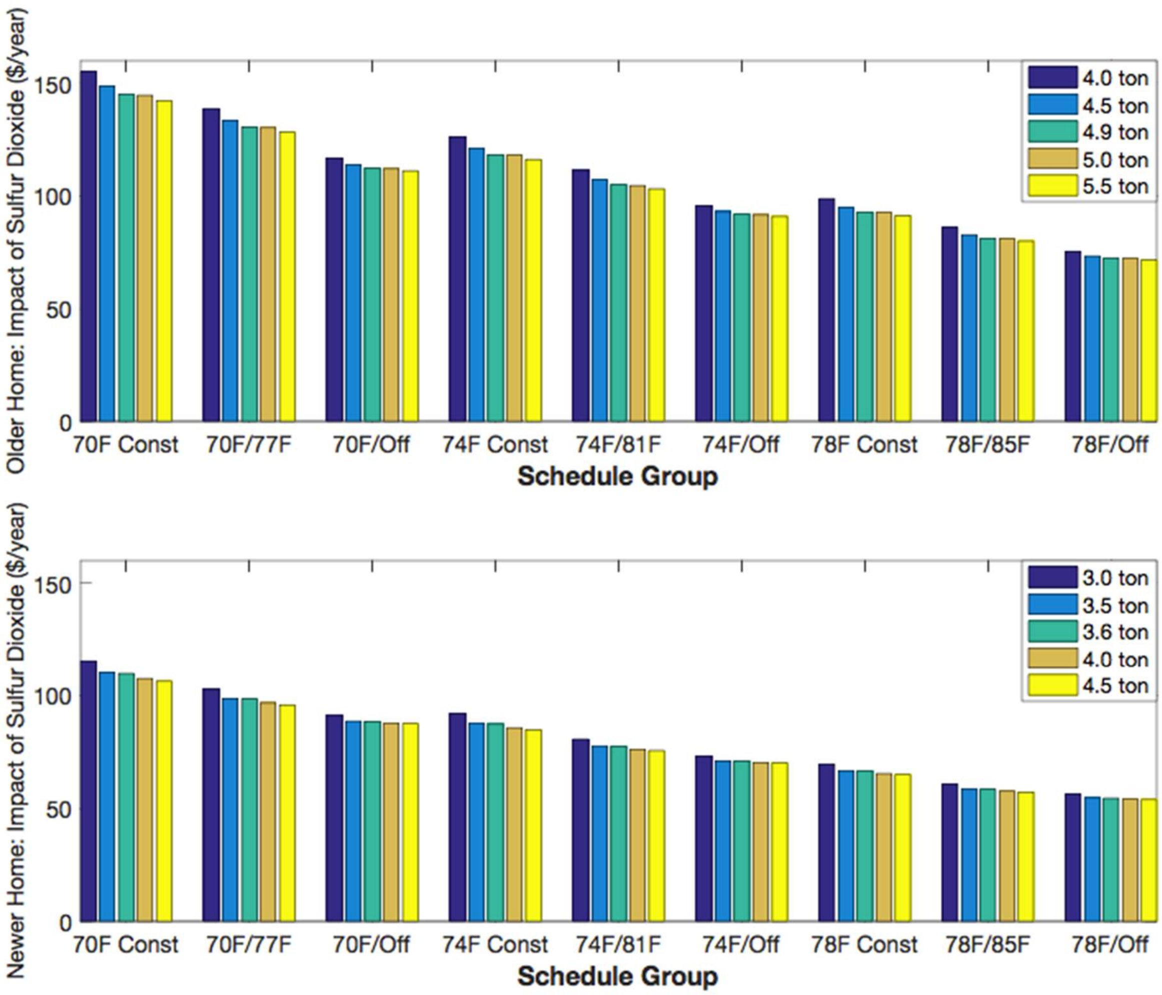

Figure 17: Impacts in dollars for yearly sulfur dioxide emissions

Although there were less than 2 kg/year per house, the APEEP modeled social cost for sulfur dioxide at nearly a 1,300% increase, or $104, over the social cost of particulate matter for the older home on average.

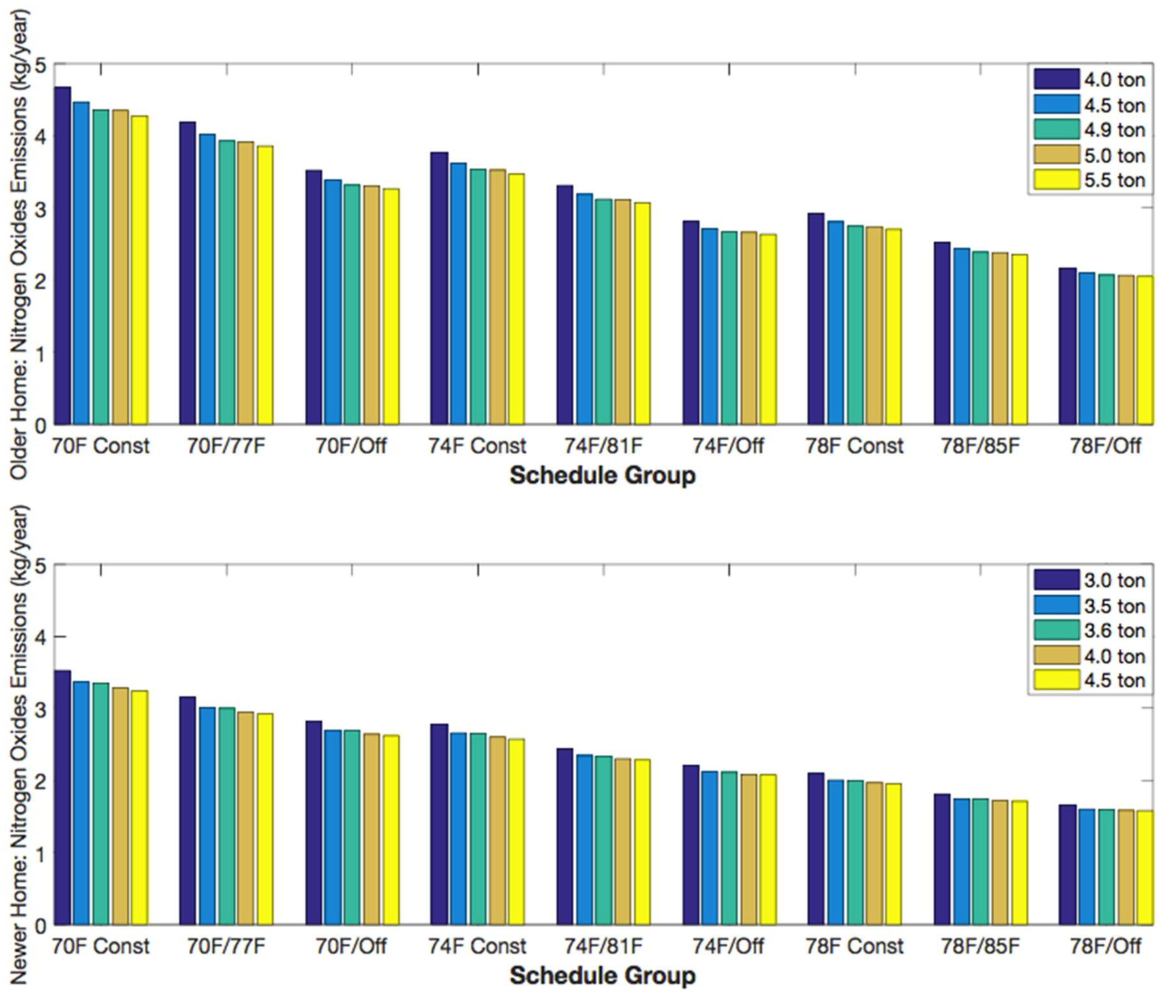

Figure 18: Marginal nitrogen oxides emissions for all scenarios

Nitrogen oxides were produced in the range of two to five kilograms per year. The amount generated was more than sulfur dioxide (<2kg/yr), but still much less than carbon dioxide emissions (>2,000kg/yr).

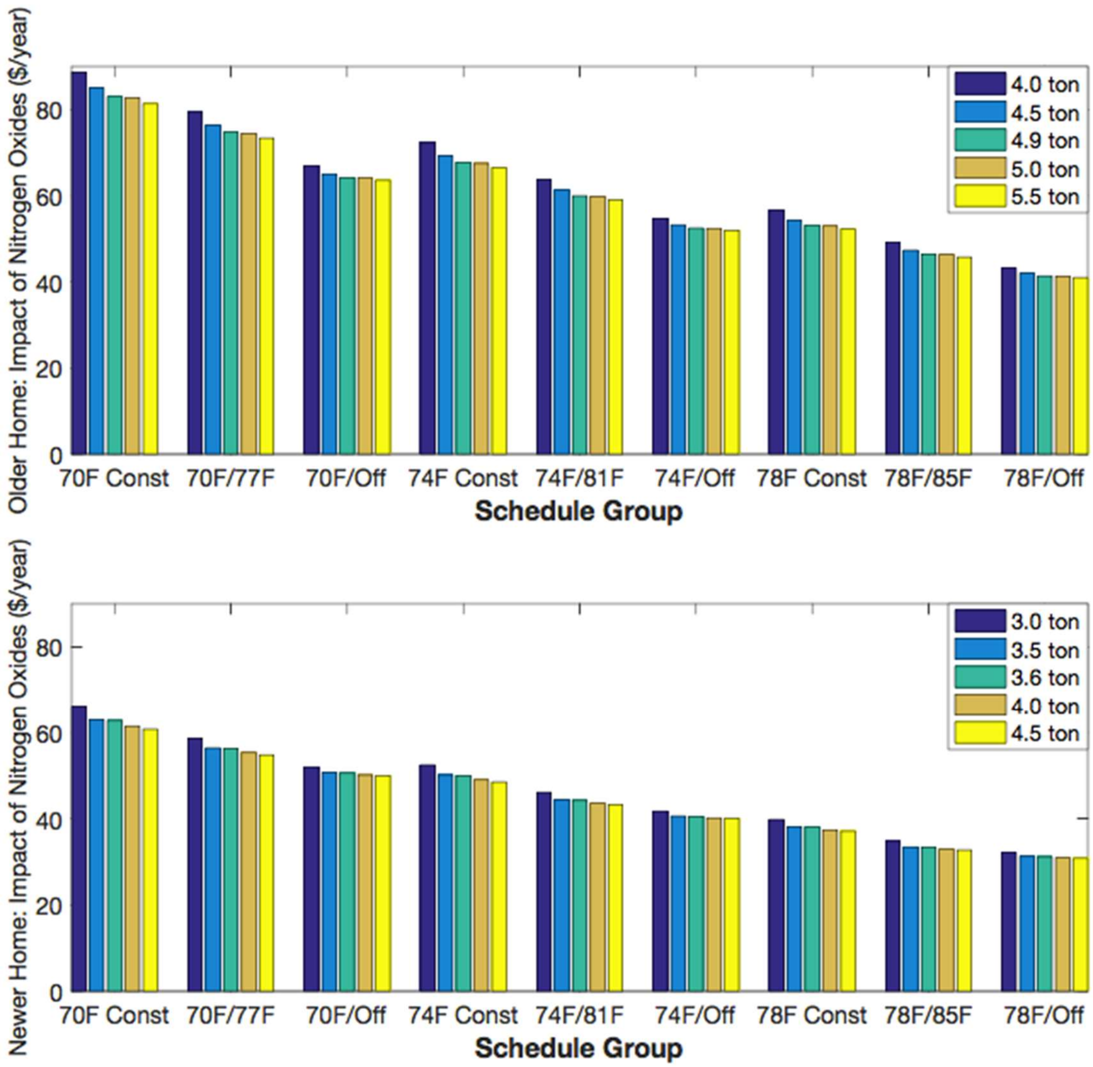

Figure 19: Impacts in dollars for yearly nitrogen oxides emissions

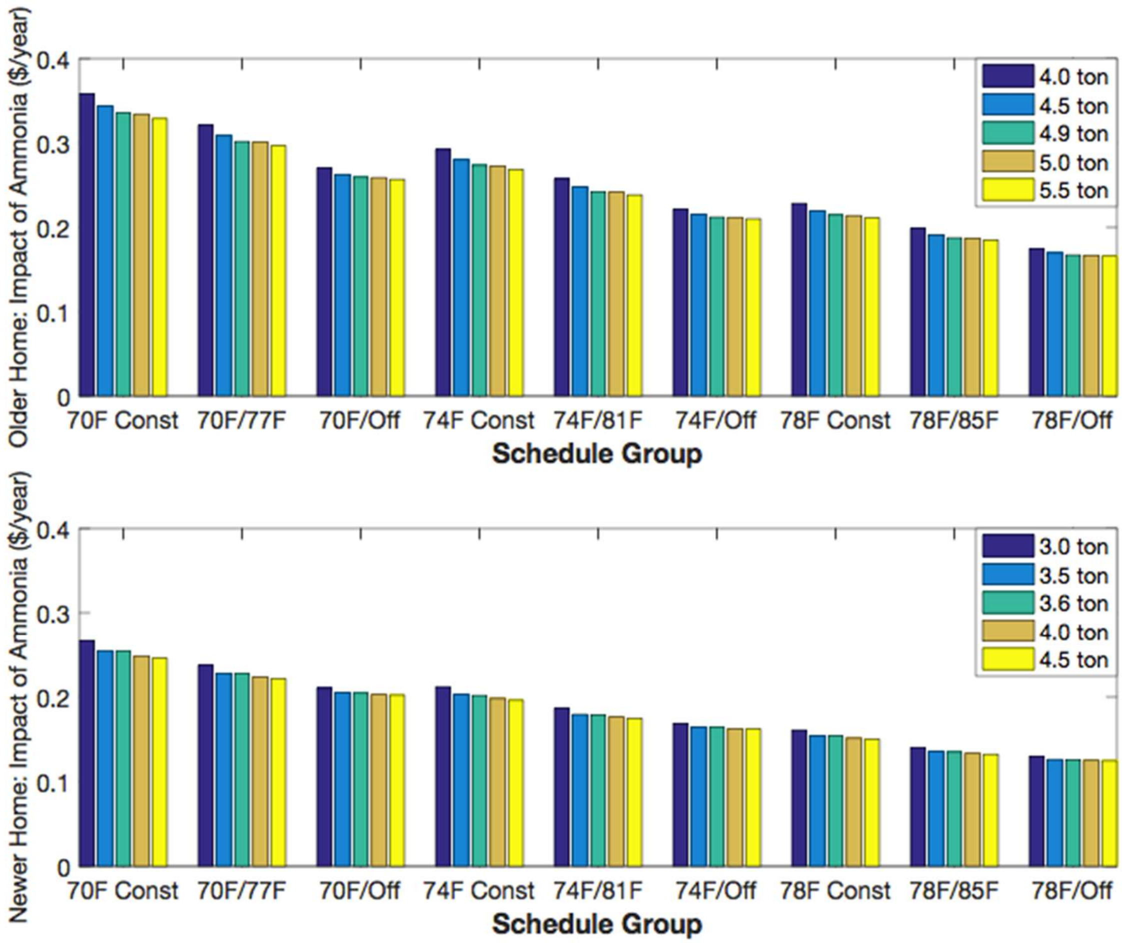

Figure 20: Social impact in dollars of ammonia emissions for all scenarios

The annual social impact for ammonia ranged from just over a dime to under 40 cents. The minimum cost across the 1.2 million older homes is about $240,000 for the Phoenix region. The social impact of VOCs was the lowest among the five APEEP pollutants, remaining under $1/yr.

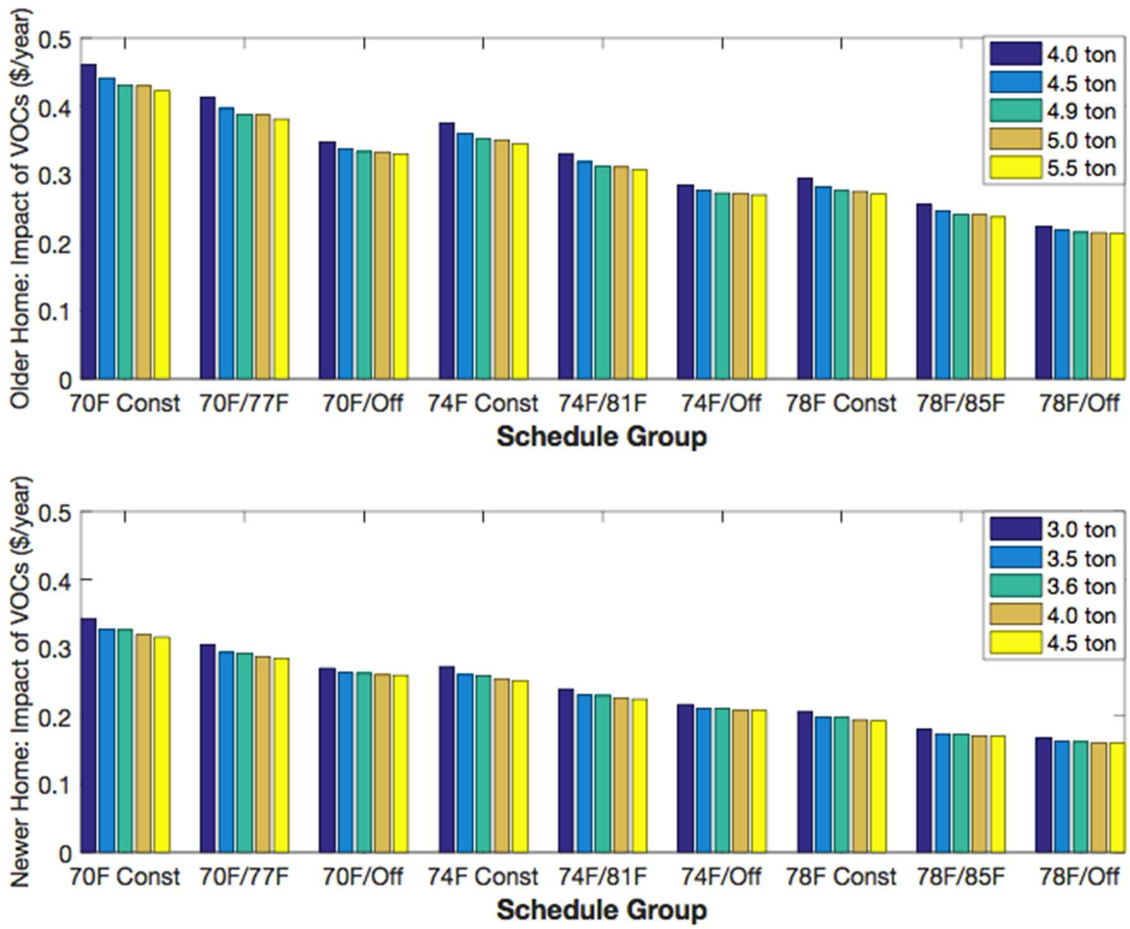

Figure 21: Impacts in dollars of yearly VOC emissions

6.3.2 Total Social Cost

The two scenarios that bookend the range of results were the 70°F constant and 78°F/"Off" schedules. As seen in Figure 22 and Figure 23, the costs to homeowners and costs from emission had similar trends. Total societal costs (TSC) are clearly driven by utility costs. As for the impact of schedules on cost, "Constant" schedules had the opposite effect of setback schedules in terms AC system size-cost interaction.

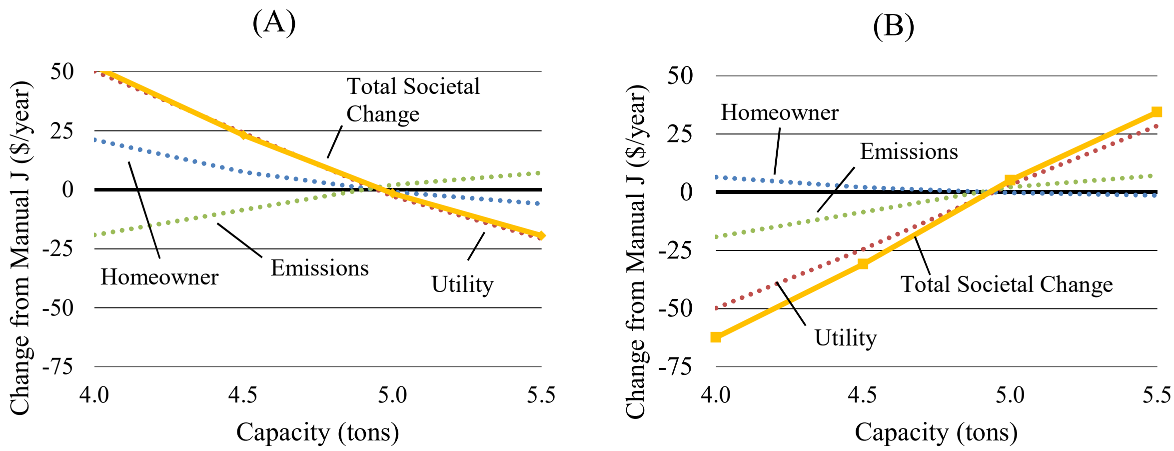

Figure 22: Older home: The change in overall total societal cost (TSC) components relative to the Manual J baseline for its three components: utility costs (generation and peak load costs), homeowner (initial investment cost), and emissions (social cost of emissions).

The graphs of Figure 22 represent the two schedules that typically had the most extreme results, (A) 70°F "Constant" and (B) 78°F "Off". For "Constant" sizing, generation costs are lower with smaller systems, while the opposite is true for "Off" schedules. The graphs of Figure 23 represent the two schedules that typically had the most extreme results, (A) 70°F "Constant" and (B) 78°F "Off". For "Constant" sizing, generation costs are lower with smaller systems, while the opposite is true for "Off" schedules.

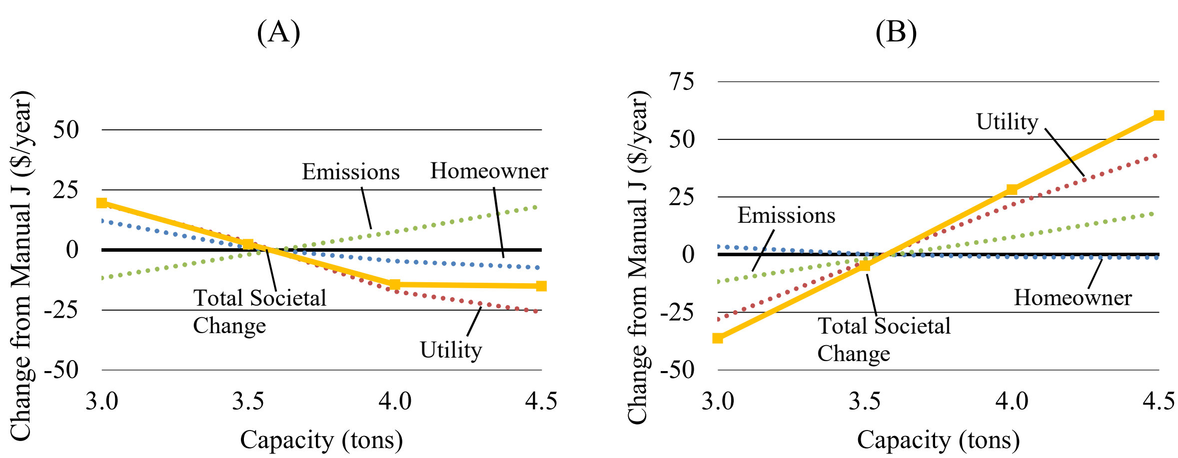

Figure 23: Newer home: The change in overall total societal cost (TSC) components for the newer home relative to the Manual J baseline for its three components: utility costs (generation and peak load costs), homeowner (initial investment cost), and emissions (social cost of emissions).

Clearly, there are various tradeoffs between sizes for each stakeholder. For smaller sizes, homeowners will have increased unmet loads and mostly higher net present costs. On the other hand, peak load costs for the T&D utility are lowered while also experiencing increased electricity sales due to higher electricity usage. However, cost to generate power increases slightly and society experiences larger social costs due to pollution. For larger systems, the opposite is true. Homeowners experience lower NPC and reduced unmet loads while utilities have lower electricity sales. Higher peak load costs to the T&D utility drive up costs to society as a whole.

7. Discussion

Each stakeholder has different metrics, goals, and motivations. The first section explores each of the results presented in the previous section as individual output metrics that can contribute to a larger picture of interactions. These factors are then woven together to consider a holistic view for each stakeholder in the next section.

7.1 Impacts of Individual Output Metrics

The results for each output metric are analyzed individually by finding trends, expected and unexpected outcomes, and the first look at what is important to each stakeholder.

7.1.1 Energy Consumption and Electricity Cost to the Homeowner

From Figure 10, as the number of hours at a higher set point temperature increases, the amount of power consumed decreases. The same is true for increasing capacity, contradicting results from the previously mentioned study from James et al. (1997) [30]. The overall lowest consumption was seen with schedules that have a starting set point of 78°F as it correlates more strongly with outdoor temperatures, which shortens system runtime. This effect is due to the decreased difference in indoor and outdoor temperatures. The newer and older homes followed similar trends although the magnitude of different consumption patterns was larger overall for the older homes. The largest capacities modeled for each newer and older home respectively were the 4.5-ton and 5.5-ton and used the least electricity across all schedules. This was not expected since the usual guidance is that oversizing leads to increased electricity consumption, and multiple institutions recommend against contractor oversizing. Figure 4 shows power consumption over time of the smallest and largest capacities modeled for the older home during an off schedule. As Figure 10 showed, more total energy is consumed by the smaller rather than the larger system. Bigger systems use more power initially and smaller systems are on for a longer period. Smaller capacity systems are less efficient at cooling and need to run longer to achieve the same amount of cooling.

The Manual J capacity was not the most energy efficient option for any scenario. For both homes, the most energy efficient choice was the 78°F/Off schedule with the highest capacity system while the most energy intensive option was the 70°F constant schedule with the lowest capacity system. The range of power consumption was 3,872 kWh to 8,294 kWh for the newer home and 5,149 kWh to 11,140 kWh for the older home. By schedule type, generally the amount of energy consumption in ascending order was the off setback schedules, the seven degree setback schedules and the constant schedules. Therefore, homeowners looking to save should choose off schedules.

The cost of running a system is important to a homeowner. The data in Figure 24 is arranged to represent options for the owner of an older home for the schedule most beneficial to them, given their temperature setting preference for the capacities represented. In order to spend less than $900 over the year, only six schedules can be used: three Off setbacks, two Plus Seven setbacks, and one Constant setting. If the desired starting temperature is 70°F, only the off schedule can be used. There are two schedule type options for the 74°F starting temperature and all three schedule types can be used when starting at 78°F. From the graph, homeowners can choose which systems work best for their preferences. The cost of running the system is important in terms of monthly payments to the electrical utility, but this data does not show the cumulative costs of owning the system over its lifespan. The net present cost includes the cost of electricity over the system's lifetime, initial purchase cost, and installation cost and is discussed in 7.1.3 Net Present Cost.

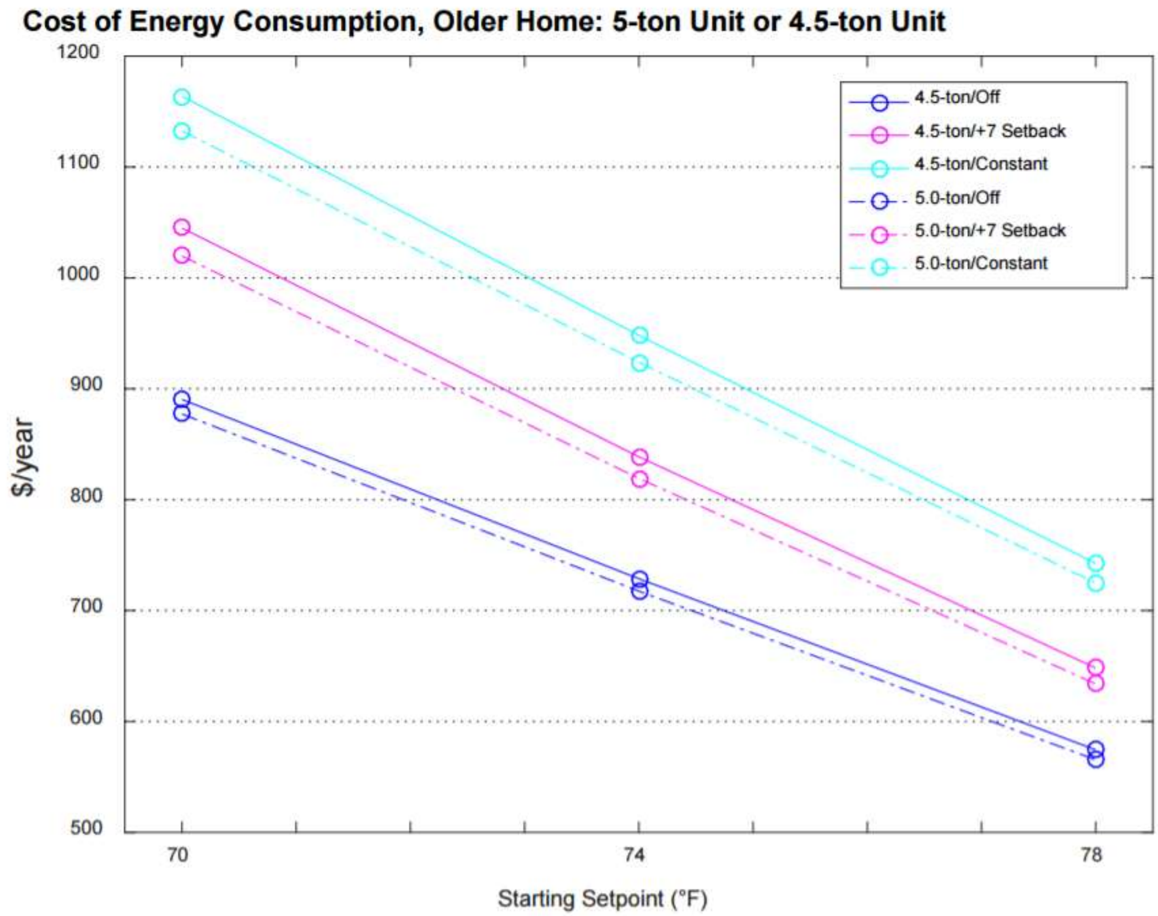

Figure 24: Comparing costs for a 5-ton & 4.5-ton system across schedules in an older home

7.1.2 Unmet Loads

As seen overall in Figure 10 and Figure 11 the larger the capacity, the fewer unmet loads are experienced. This was expected, as a major reason for AC oversizing is because it guarantees fewer unmet load hours, ensuring customer comfort. The magnitudes of the unmet loads, as expressed in degree-hours, were also lower for the larger systems. Figure 25 and Figure 26 show how two setback schedules, 70°F/Off and 70°F/77°F, distribute unmet loads differently when reaching their evening set point temperature. The off schedule has higher indoor temperatures when the occupant is expected to be home and for a longer period overall. This schedule could potentially become uncomfortable for the occupant since by 7PM for the Manual J size system, the temperature only lowered to 79°F for the Off Schedule whereas the indoor temperature was eight degrees lower for the Plus Seven Schedule.

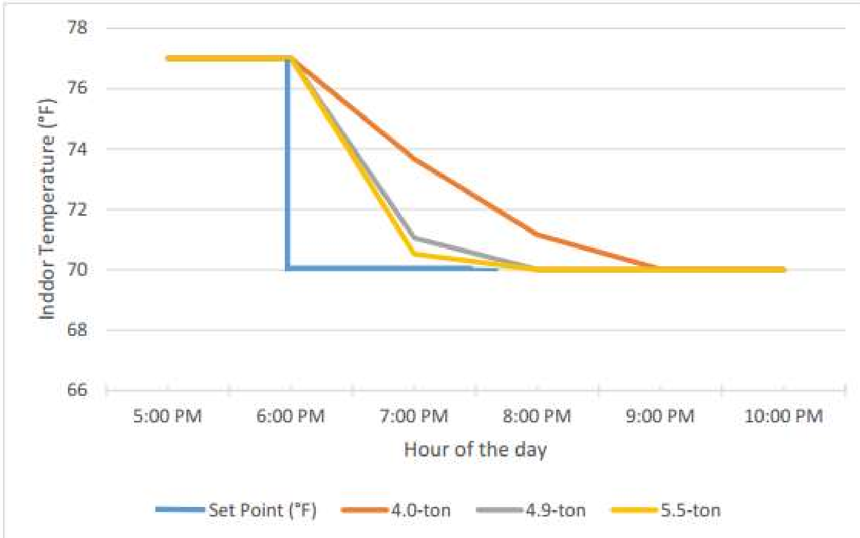

Figure 25: Three capacities running to meet the set point in the older home for a 70°F/77°F setback schedule

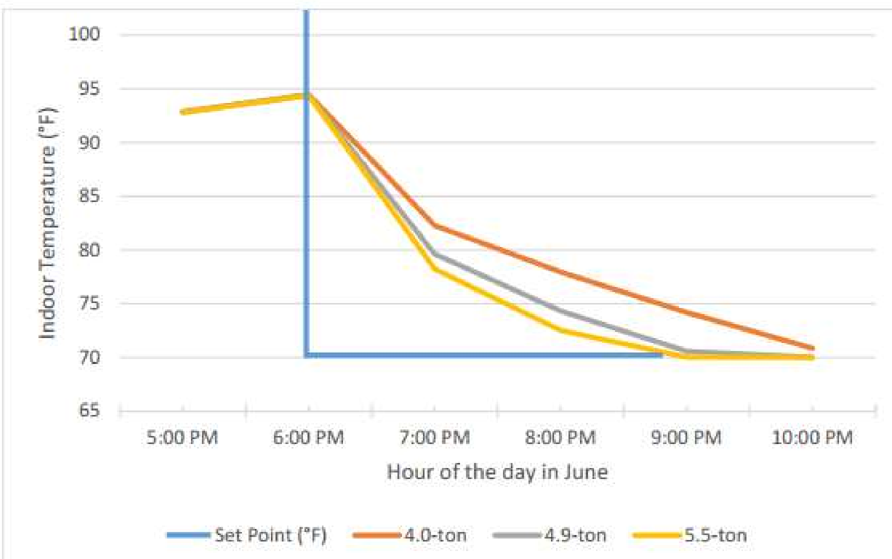

Figure 26: Three capacities running to meet the set point in the older home for a 70°F/Off setback schedule.

A major factor in choosing a capacity based on unmet loads is schedule type. For constant schedules, all capacities provided the same level of comfort with almost zero unmet loads or degree-hours. The smallest systems were too inefficient to provide no unmet loads, but the effect was minor at under 10 unmet hours. For the setback schedules, the capacity that provided the lowest number of unmet loads was always the largest capacity. Unmet loads were higher for the off schedules, although the homeowners will pay less for electricity when using off setback schedules. These conclusions hold true for both older and newer homes. When comparing the plus seven setback schedules to the off schedules, there is a potential for major savings of unmet load hours. In the older home, moving from off schedules to plus seven set back schedules decrease unmet load hours from anywhere between 60% to 100%.

To illustrate the distribution of unmet loads for this schedule during the year, Figure 27 shows the set point and indoor temperatures for sample days from summer months for the Manual J sized system in the older home using the 70°F/Off schedule. Clearly, most unmet loads occur during the hotter months of the year. When the occupant returns at 6PM, all temperatures were in the 90s except during May. At 7PM, an hour after the occupant returns home, the hottest month of July had an indoor temperature of 83°F, 80°F in August and June, 79°F in September, and in May the set point was reached. Depending on the tolerance of the homeowner, a range of indoor temperatures will be experienced for an off schedule. Unmet loads correlate to increased maximum indoor temperatures as seen in Figure 28, which could affect a homeowner's capacity choice if they have electronics, sensitive instruments, or pets in their home.

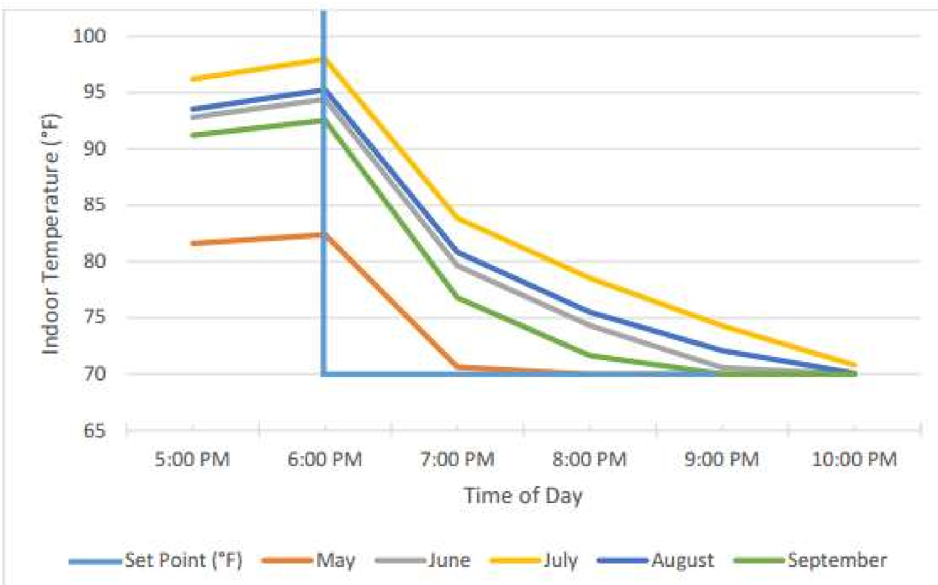

Figure 27: The indoor temperature of the older home using a 4.9-ton system during the second week of each summer month for the 70°F/Off schedule.

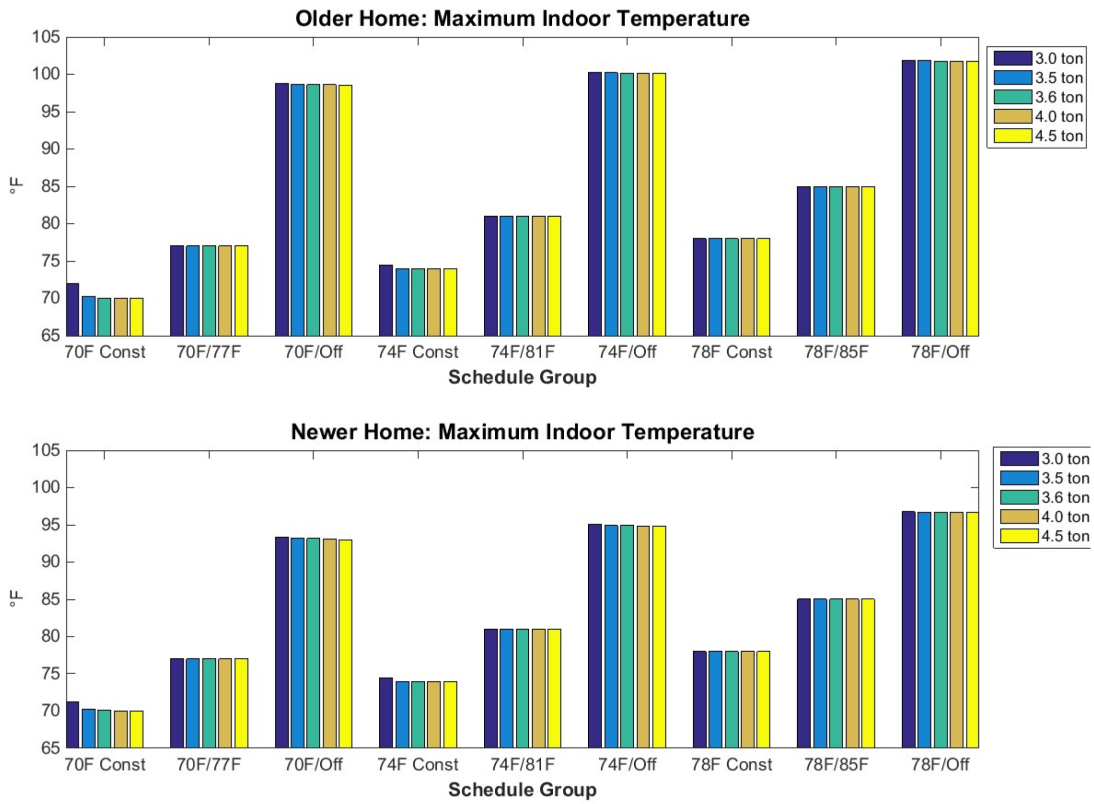

Figure 28: Maximum indoor temperatures for all combinations

As setbacks were the only schedules with unmet loads, the question becomes whether there can be a setback schedule that does not have the tradeoff of unmet load hours. In order to understand how impactful the setbacks are and how they may change such that the desired comfort of a homeowner can be achieved, additional analysis was performed. We looked at delaying the setback by two hours for the schedule with the biggest unmet loads, the 70°F/Off schedule, and for the schedule with no unmet loads and an additional economic cost, the smart thermostat. First, additional simulations were run for a schedule that allowed for precooling by two hours for the older home. Instead of the weekday 8am-6pm setback of 10 hours there was an 8am-4pm setback of only eight hours. Results for the Manual J sized 4.9-ton system are shown in Figure 29 and are in terms of the indoor temperatures of the home in the middle of summer.

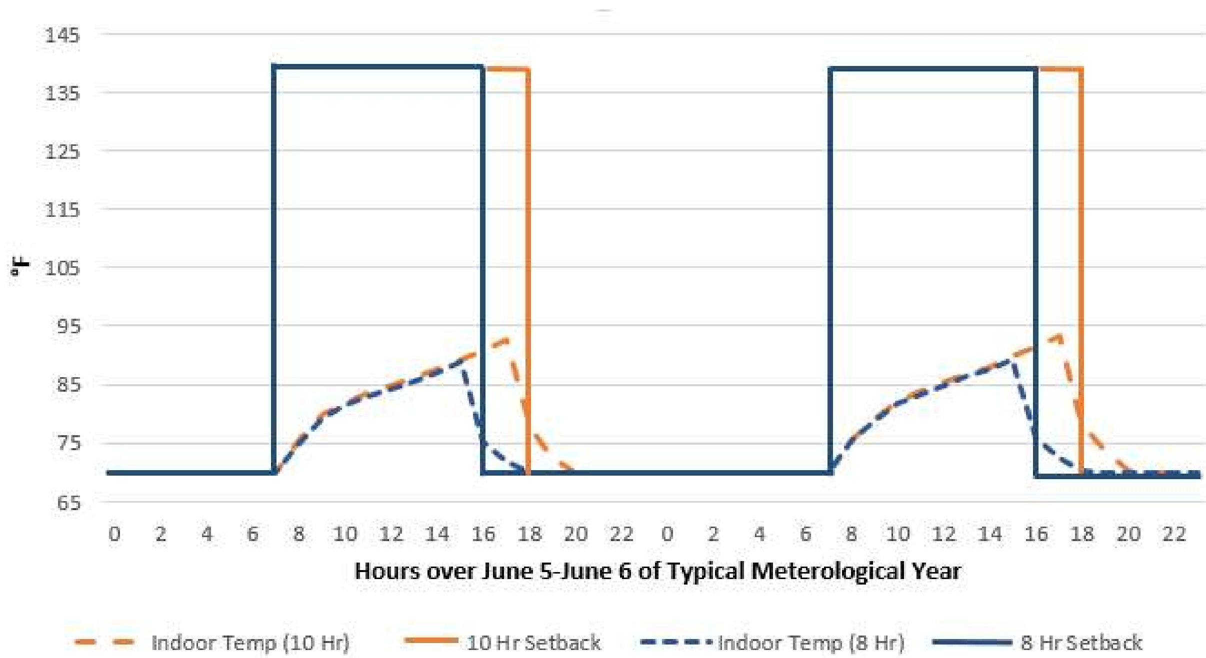

Figure 29: Comparing earlier setback for the 70°F/Off schedule at 4.9-tons in the older home over two summer days

Using the Manual-J size AC system, Figure 29 shows that starting cooling two hours sooner results in zero unmet loads by 6pm, when the occupant returns. This was not the case with any off schedule with the 10-hour setback. We assume other off schedules would also experience this reduction of unmet loads because the modeled schedule consistently had the most unmet loads. Also, the number of unmet loads is smaller overall with the shorter 8-hour setback since the ACs run less as the indoor temperature does not increase as much as with the 10-hour setback. For the 8am-6pm schedule, an indoor temperature of 70°F is reached at about eight o'clock, while the temperature at 6pm is in the upper 70s. Table 7 shows the results for all the tonnages over the entire year as well as the difference between them. Included is the change in volumetric consumption.

Table 7: Comparing annual unmet loads and electricity consumption by switching from a 10-hour (8am-6pm) to 8-hour (8am-4pm) setback schedule in the older home using the 70°F/Off schedule.

Capacity	Avoided Unmet Loads (degree- hours)	Reduction in Unmet Loads (%)	Increase in Electricity Consumption using 8-Hour setback (kWh)	Incremental Cost of using 8-Hour setback ($)
4.0 ton	1,665	-4	894	97.44
4.5 ton	1,575	3	882	96.16
4.9 ton	1,629	9	871	94.88
5.0 ton	1,570	10	871	94.88
5.5 ton	1,281	19	856	93.28

Overall, when switching from the 10-hour to the 8-hour setback, electrical consumption increased and unmet loads decreased. The 4.0-ton system did not match the rest of the capacities. The 4.0-ton system increased in unmet loads when switching from the ten to the 8-hour setback since there was two more hours for which the small system could not sufficiently cool the home. For the rest of the capacities, switching from a 10- to 8-hour setback meant that unmet loads decreased because the system was running longer, as seen in the increase of electricity consumption in the last column of the table. The increase in electricity consumption averaged 874.6 kWh, which translates into about $95 more per year. Which setback the homeowner chooses depends on what they value more, either $100 in their pocket or comfort when arriving home. Interestingly, the extra cost is constant across capacities while the actual difference in unmet loads varied greatly depending on system size. For example, shaving off two hours of run time for the 5.5-ton system increases consumption by 855 kWh, which is comparable to the 882 kWh increase for the 4.5-ton system. However, the 5.5- ton system reduces unmet degree-hours by 257.3, which is almost four times the 72.2 degree-hours reduction using the 4.5-ton system. Since the longer 10-hour setback had more unmet loads, it follows that the average hottest indoor temperature across all capacities was higher for the 10-hour setback at about 99°F and was 95°F using an 8-hour setback.

Tradeoffs between power consumption and unmet loads can be further observed by simulating shorter setbacks (6-hour, 4-hour, 2-hour, constant temperature) for the 4.9-ton system with the same 70°F/Off schedule that had the highest unmet load hours. Another option to reduce unmet load hours is to own a smart thermostat. All of these schedules were simulated as follows. For the six through two-hour setback, BEopt simulations were run using the same methods as for the 10- and 8-hour setbacks. The 4.9-ton Manual J size was modeled since it can be considered middle of the range as the unmet loads and electricity usage were linear between capacities when comparing the 10-hour and 8-hour schedules. A basic smart thermostat was modeled using a spreadsheet and the following method. Starting with the original 10-hour setback data for energy consumption and indoor temperature, the hours needed to reach the set point temperature was calculated with a tolerance of 1°F. For every hour that was unmet, the energy usage was shifted up an hour. In order to keep the same slope of energy usage decline as the indoor temperature reached the desired temperature, the energy consumption from not only the unmet hours, but also the following two were shifted as well. If there were three unmet hours in a row, then five hours of energy usage were shifted up three hours. The energy usage of the last shifted hour of the group was used to fill in any gaps and maintain the gradual decline in power consumption as the indoor and set points matched. In this way, there would be no unmet loads while using a setback schedule and an approximate amount of energy consumption could also be observed. The results of these simulations are seen in Figure 30.

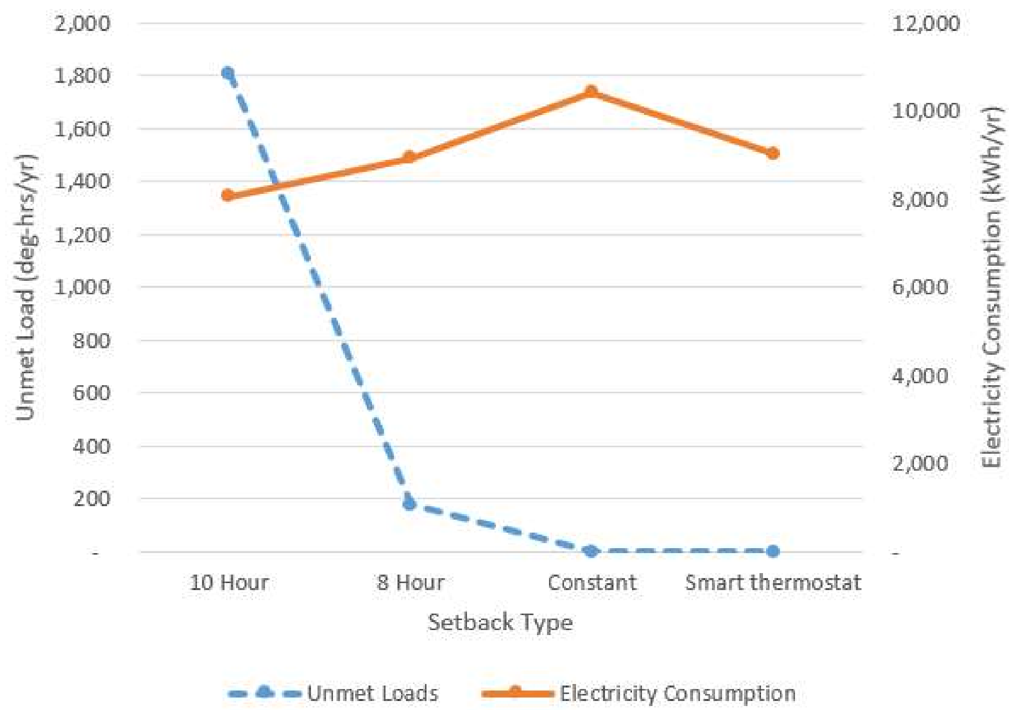

Figure 30: Unmet Loads (deg-hrs/yr) and Electricity Consumption (kWh/yr) for a smart thermostat and various hours of setback for a 70°F/Off schedule in the older home, using the middle range 4.9-ton Manual J size.

For the simulated year, the smart thermostat provided zero unmet load using 9,019 kWh. At 1,641 degree-hours, the 8-hour setback has a huge comfort level tradeoff while having a comparable electricity usage of 8,930 kWh, only 89 kWh difference. As electricity consumption is directly proportional to the cost of electricity per year at 10.9 cents/kWh, using the smart thermostat will cost $10 more than the 8-hour schedule and about $100 more than the 10-hour schedule as seen in Table 8. As previously discussed, the results in Table 4 show that generally as capacity increases, both unmet loads and electricity usage decrease. However, the rate of decrease for electricity consumption is almost constant. It changes by the range 850 kWh to 900 kWh across all capacities. Since the smart thermostat was modeled with a 4.9-ton system, which is in the middle of previously modeled capacities, electricity usage and unmet load capacity trends seen in Table 4 would be applicable. Choosing a capacity either a half ton larger or smaller would result in similar effect for other tonnages that use the smart thermostat schedule.

Constant schedules were the only schedules to have no unmet loads, no matter the capacity of the system, unlike the other setback schedule types (plus seven degrees and off). The smart thermostat removes this tradeoff by ensuring zero unmet loads when the home is occupied while also saving about $150 in electricity costs per year against the constant schedule. This does not include the increase in avoided emissions since using a setback schedule means that peak hours will be avoided. Also, since smart thermostats range in price from $100-300, the average payback period would be less than two years. In fact, using the 8-hour setback is comparable in electricity consumption to investing in a new smart thermostat, at around 9,000 kWh per year. A smart thermostat is the only way to avoid the unmet load tradeoff, for any sized system, while still benefitting from the other positive effects of a setback schedule.

Table 8: Results from using a smart thermostat and various setback schedules.

Schedule Used to Maintain 70°F Indoor Temp.	Unmet Loads (degree-hours/yr)	Electricity Consumption (kWh/yr)	Cost of Electricity Consumption ($/kWh/yr)	Savings Using Smart Thermostat ($/yr)
10 Hour Setback	1,808	8,060	878.52	(104.55)
8 Hour Setback	1,641	8,930	973.40	(9.67)
6 Hour Setback	847	9,692	1,056.43	73.36
4 Hour Setback	213	10,154	1,106.79	123.72
2 Hour Setback	21	10,363	1,129.57	146.50
Constant	-	10,420	1,135.78	152.71
Smart Thermostat	-	9,019	983.07	-

7.1.3 Net Present Cost

Overall, Net Present Cost (NPC) had variable results compared to the cost of energy alone as seen in the Section 7.1.1. This outcome is due to the included fixed costs of installation and purchase price that do not rise with the amount of electricity consumed. For example, in the newer home, the worst economic choice was usually either the smallest capacity system or the largest capacity system. The smaller capacity system drove up costs from electricity usage, as it had to run constantly to keep up with the demanded load. For larger capacities using less energy, the decrease in economic attractiveness was driven by a higher initial investment of the cost of the system itself. The larger capacity systems became the least economical for the most energy saving off type schedule groups, but only by about $100 over the entire lifespan. In fact, all results showed less than $100 savings among each schedule group. Therefore, choice by the homeowner of one capacity over another is not influenced by NPC, as the cost is mostly flat across each schedule group.

Since the NPC is limited in its influence over a homeowner's choice in AC capacity, motivation could come from other factors. A homeowner can choose a thermostat schedule to not only save money but, given their preferred setback schedule, save on unmet loads. Homeowners might choose a larger system over a smaller one to avoid unmet load hours during which the capacity cannot reach the desired indoor temperature due to a smaller system's inefficiencies. To better understand this tradeoff and by how much unmet loads could influence a homeowner's choice, the intensity of unmet degree hours per $100 dollars of NPC is seen in Figure 31 for the schedule with the largest unmet loads, 70°F/Off. The smallest capacity system for the new home has about 32 unmet degree-hours for every $100 of NPC. That is much costlier than the largest capacity system that is three times less expensive at 10 degree hours per $100 of NPC. Both homes share the same trend with the largest capacities providing fewer unmet degree-hours for the same amount of NPC and the smallest capacities allowing for more missed degree-hours.

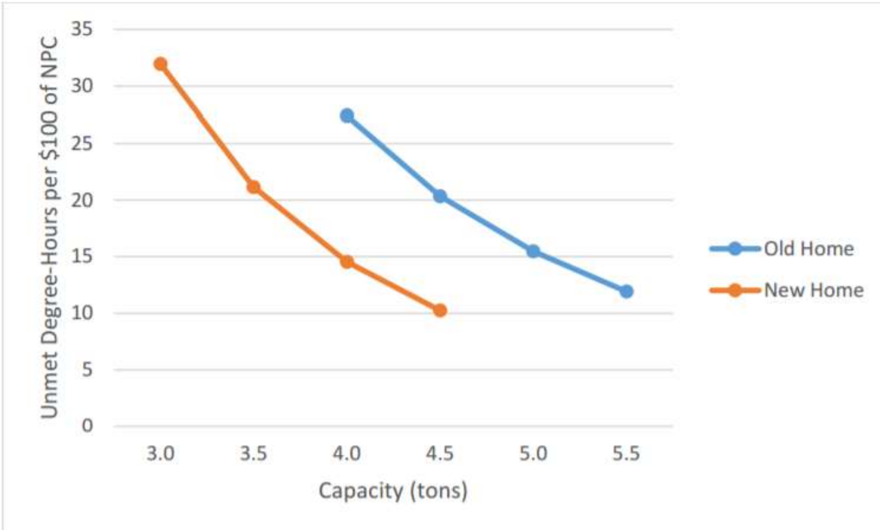

Figure 31: The number of unmet loads as expressed in degree-hours for every $100 of net present cost, arranged by AC system capacity. Data is for both homes and the 70°F/Off schedule group that had the largest unmet loads of any schedule group.

Another means through which a homeowner can be influenced other than by NPC are through subsidies. A utility can influence the choice of the homeowner economically through subsidies to purchase one size over another. If the local T&D utility prefers the homeowner to have a smaller system, for example, they may provide incentives that would lower the NPC for the smaller systems to the point where it makes economic sense to purchase that system instead. However, there will be increased unmet loads with smaller systems that can sway the homeowner back to the larger capacities. The subsidy options are determined by which size the utility prefers a homeowner to have and are explored in the next section.

7.1.4 Cost of Generation

The cost of generation is important to utilities because it provides information about peak consumers and therefore peak loads. As described in the Background section, regulators, power generators, and transmission and distribution utilities want to reduce peak load for efficiency purposes that result in higher economic savings and better future investments. By knowing which customers to focus on, energy savings campaigns can be more beneficial. For example, Figure 13 demonstrates that different tonnages within a schedule make arguably no difference to costs. However, as the desired starting set point temperature of each thermostat schedule increases, generation costs decrease. Costs also decrease when moving from constant, to setback, to off schedules consecutively. Therefore, regulators and utilities can cut costs by encouraging the use of any setbacks, especially off schedules.

As seen in Figure 32, for all schedules in both types of home, the generation cost is consistently between 46% and 49.5% of the total price the consumer pays the utility for electricity. The lower this percentage, the better off the generating utility is because it means they are spending less to generate the electricity that a customer is using. Lower generation cost for a given energy price, means wider profit margins, if it remains within the limits allowed by law. Clearly, the smaller capacities, especially during off schedules, provide the most profit potential for the utility as generation costs are lower for them. Off schedules do not use electricity during the day, which is when prices are generally higher as discussed in the Background. The schedules use electricity at peak times like 5PM as do all the modeled schedules.

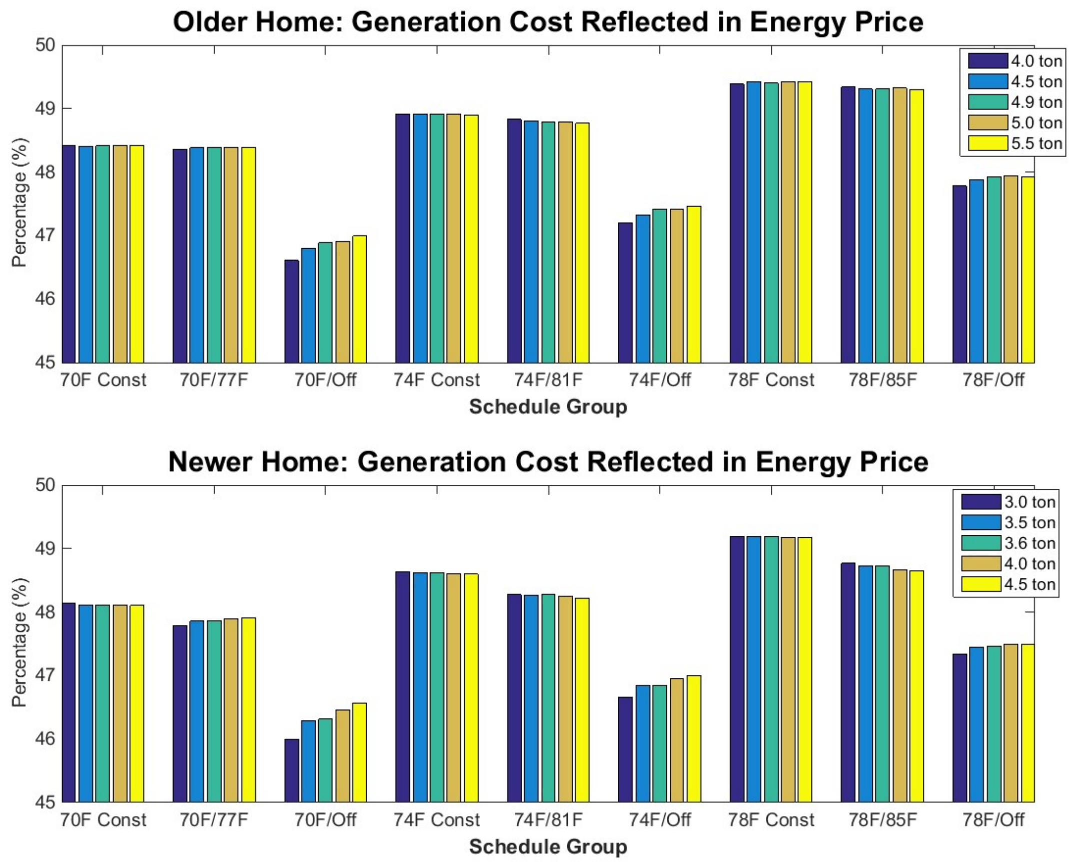

Figure 32: Annual generation cost as a percentage of the price of electricity consumption for both house types.

7.1.5 Peak Load Costs

Higher tonnage AC systems have the capacity to use more energy at any point in time. Therefore, one can expect that reducing their usage would be more valuable to peak load managers than reducing the usage of smaller sized systems. This is reflected in Table 5 and Table 6, where the smaller tonnages are less costly. The difference between the minimum and maximum peak load costs between the largest and smallest capacities was about $100 for the older and newer homes at $97.70 and $99.80, respectively. The older home had a higher peak load cost by 23.4% percent over the newer home. Not considered within peak load costs are the savings from avoided transmission and distribution losses.

7.1.6 Marginal Emissions Factors

Plans to reduce carbon dioxide emissions are often in the form of energy conservation, efficiency and more recently carbon capture and storage. As previously explained, the energy mix of a region controls the percentage of fossil fuels burned and therefore the amount of pollutants such as carbon dioxide released into the atmosphere. As Arizona has a fossil fuel heavy energy mix, the results correlate to the amount of electricity used.

The purpose of using marginal emission factors was to demonstrate additional emissions if the AC systems were to use electricity from the grid today. Figure 14, Figure 16 and Figure 18 show that the lowest emissions come from the largest systems for CO_2, SO_2, and NO_x. For example, using a larger over a smaller system results in lowering carbon dioxide emissions by 4.8% to 8.3% in the older home and by 3.9% to 8% in the newer home. Those percentages translate into an average of 271 kg for the older home and 178 kg of CO_2 for simply switching to a larger capacity system. For example, in the 78°F/Off group, the number of kilograms released per year varies by 127 kg between the smallest and largest systems in the older home. Since one gallon of gasoline combusted by a car generates about 9 kg of carbon dioxide, the 127 kg CO_2 difference in emissions is equivalent to burning about an extra 14 gallons of gasoline for using a smaller AC system over the year. Switching from a large to a small system at the 70°F constant schedule in the older home makes a difference of 455 kg. If a car's gas tank takes about 13 gallons of gasoline on average, that means filling up the tank two extra times per year. However, the major driver of emissions for AC systems is not capacity, but schedule choice. This result is key for policy makers within the regulating bodies.

According to the EIA's 2009 Residential Energy Consumption Survey data, there are about 1.2 million single-detached housing units in Arizona. These homes are more likely to match the characteristics of the simulated older home characteristics, as the newer home is based on standards of building from the year 2010 and beyond. These savings become much larger when considering these homes. For example, if each of the nine schedule types were split evenly across those 1.2 million people, about 133,333 would prefer the 78°F/Off schedule and possibly one-fourth of that group has large capacity systems. According to EPA data [87], those 33,000 homeowners could collectively remove carbon dioxide emissions that would be equivalent to removing 1,171 passenger vehicles from the road by switching to the largest capacity. Emissions scale directly with energy consumption. The emissions intensity in terms of kilograms of all three pollutant emissions per 1 kWh across capacities were almost the same for all 90 scenarios. All within one hundredth of each other, they ranged from 0.491 kg of emissions per kWh through 0.486 kg of emissions per kWh. The emissions intensity was the same across capacities in the constant schedules and plus seven setback schedules, whereas the results were variable for the capacities for the off schedules. Emissions intensity per 1 kWh decreased as capacity increased for the 70°F/off setback schedule, were mostly flat across the 74°F/off schedule and increased with capacity for the 78°F/off schedule.

These relationships hold for both sulfur dioxide emissions as well as those of the nitrogen oxides. The lowest emitting scenario was the same largest system with a 78°F/Off schedule at 0.869 kg/year in the older home. The range of the sulfur dioxide emissions were 56 grams across the schedule group. In the newer home, the lowest emission was 0.674 kg/year, a difference of 0.195 kg between the two home types. With nitrogen oxides, the least polluting scenarios were releasing 2.05 kg/year and 1.58 kg/year while the most were polluting 4.7 kg/year and 3.5 kg/year for the older and newer homes respectively. These results may seem small but these two compounds are responsible the creation of acid rain, which damages plants, animals and material infrastructure, including exposed metal and paint [88], [89]. The impacts through social costs of these pollutants are explored in the section that follows.

7.1.7 Social Costs

A clear trend for this region is that larger capacity systems have lower social costs across all pollutants modeled by APEEP. The schedules that have the greatest number of hours with a higher set point temperatures also do well. In this way, again, the 78°F/Off schedule with the largest capacity carries the lowest social cost. The marginal effects of choosing one size or schedule over another can be determined. For example, for the Manual J calculated tonnage of 3.6-tons for a newer home, running close to the Manual J calculation of 75°F constantly, the 74°F constant schedule has a social cost for particulate matter of $6.40/year. Choosing this option over the cheapest option for this home as presented in Section 7.1.3, the 4.5-ton with at 78°F/Off schedule, is only $3.95 per year. That is $39 over the lifespan of the system just for choosing a different AC system and schedule combination.

Most of the social impact costs due to pollution can be avoided by switching schedules in the older home. Keeping the Manual J recommended size of 4.9-tons and using 74°F constant schedule, the schedule closest to the ACCA design temperature of 75°F constant to compare to the 78°F/85°F setback schedule, results in a lifespan savings of $596 for sulfur dioxide and $340 for nitrogen oxides. Including the social savings from particulate matter, volatile organic compounds and ammonia, across the 1.5 million people who have similar home structures translates into regional social impact savings of about $1.47 billion dollars. Clearly, the choice the individual homeowner makes for how to run their system can make a collective difference. The same comparison for just three pollutants in one newer home yields savings of $464 for sulfur dioxide, $265 for nitrogen oxides and $39 for particulate matter, with a difference of about $768 of lifespan social impacts for those three pollutants.

Because the results presented in Section 6.3 are based on data from 2008, emissions are slightly higher than what they would be in 2016. The energy mix in Arizona has changed between 2008 and 2014, with a decrease of 12.7 million megawatts of electric capacity generated by fossil fuels, an increase of nuclear by 3 million MW of capacity and renewable energy sources by 2.5 million MW of capacity [90] over those six years.

7.2 Impacts to Stakeholders

The three stakeholders considered are the homeowners, electrical utilities, and society. The individual best options given their different interests are considered for the first two stakeholders. The Total Societal Cost, an analysis of a group of stakeholder costs, is considered to determine the best option for society as a whole.

7.2.1 Homeowners

Homeowners are assumed to care about two of the output metrics listed: the cost of the system for its lifespan and the amount of time their house is not cooled to their desired temperature. The overall goal is to minimize cost and minimize unmet loads. The best choices for the consumers are presented in terms of temperature preference, economic cost, and value of home improvements.

Homeowners find both savings and comfort with the largest AC systems. While smaller systems have cheaper upfront costs, those initial savings are offset by the lower total lifetime electricity consumption of larger systems, even when the savings are discounted into the future at a 5% discount rate. Smaller systems had higher electricity consumption due to lower efficiency (while all ACs had the same SEER rating, smaller systems require more electricity to remove a unit of heat). Overall, the size of the AC system has a relatively minimal impact to the homeowner's cost as opposed to the AC schedule. Given a 74 degree set point, for the constant schedule a homeowner could save $53/yr by switching from the smallest to largest AC system. However, significantly larger savings can be observed by switching from a constant schedule to an "off" schedule, which provides a savings of $200/yr for a homeowner with largest AC system. Unfortunately, switching to a setback schedule will save the homeowner money at the expense of comfort. The benefits of larger AC systems can be seen for the homeowner from this perspective as well. Consider switching from the 74 degree constant schedule to the "Off" schedule. Choosing the largest AC system at the 74°F/Off schedule will cause the homeowner to experience 767 DegHrs/yr of unmet loads, while the smallest AC system at this schedule would experience nearly twice as many, at 1,953 DegHrs/yr. A homeowner will most likely require a financial incentive if they are to adopt a smaller AC system for either the benefit of the utility or the good of society.

The combinations with the lowest NPC were for both 78°F/Off at 4.5-tons for the older home and 3.5-tons for the newer home. They had a difference of about $2,000 between them. The tradeoff for these cheaper combinations is unmet loads. The highest indoor temperatures reached was about 100°F in the old home and in the mid-90s for the newer home. The older home had 92 unmet load hours at 392 degree-hours, which was the lowest for the entire schedule group. Otherwise, the unmet load was comparable only to the 4.5-ton with a 70°F/77°F schedule at 90 unmet hours, with an increase of 100 more degree-hours and NPC of $5,000. Meanwhile in the newer home, the largest capacity had only 58 unmet hours at 205 degree-hours, about 200 lower than that of the old home. The comparisons of unmet loads across the cheapest options mean that similar unmet loads from similar tonnages can be achieved using different schedules, but can cost thousands more.

Cheapest capacities with lowest unmet loads in the older home were typically the highest tonnage within a schedule group, not their Manual J size. The most economical choice for the newer homes was less straightforward since it depends on how homeowners value tradeoffs. Considering all schedules, the tonnage with the lowest NPC for both house types were below their calculated Manual J value, whereas ACCA recommends sizing up from the Manual J value.

A homeowner's temperature preference has clear tradeoffs. For those who prefer it colder, within the three 70°F starting point schedule groups, the only output metric to optimize is the elimination of unmet loads by the constant schedule type, since none have a comparatively low NPC. There are fewer unmet loads for the schedules that have higher temperatures for longer periods of time. If a user prefers a warmer home, they will not only have fewer unmet loads, but also save money using one of the two types of setback schedules.

There are many recommendations surrounding programmable thermostat set points. Various sources, such as the HVAC contractors, government and advocacy groups offer different suggestions of the best way to use a residential central air conditioner. There is also literature that shows that users do not use their programmable thermostats and corresponding setbacks correctly or even at all. The data presented here shows that setbacks are only as useful as how high the homeowner allows them to be. The plus seven degree setback is a middle range option and was never the cheapest nor most expensive option. Consumers are told this is energy efficient and cheap by EnergyStar, but if a homeowner wants to absolutely save the most money or is willing to sacrifice unmet load hours, a seven degree setback schedule will not maximize their savings potential.

Occasionally energy efficiency upgrades are recommended to homeowners. For example, in the extreme case of the cheapest possible NPC combination between the 78°F/Off at 4.5- tons for the older home and 3.5-tons for the newer home, a $2,000 difference between the older and newer homes is expected over the lifetime of the system. If a homeowner wanted to pay for improvements, they should spend less than this amount in order to make a valuable investment in AC cost reduction. This improvement also has the potential to save an annual 200 degree-hours and 30 unmet load hours.

7.2.2 Utilities

The ideal residential power consumption for the T&D utilities would include the following two situations: decreasing peak load and increasing overall energy consumption. Firstly, a decrease in peak demand would be desirable for multiple reasons. Lower peak demand translates to freedom from planning for grid instability as well avoided lower profits from peaker plants, including avoided new construction costs, operations and maintenance costs. This benefit can be seen in Figure 16 as decreasing peak load costs where smaller AC systems cost T&D utilities a little less ($350/year) than larger systems ($450/year). Therefore, it is more valuable for the utility to attempt to decrease the use of the largest systems than the smaller ones during peak times since they cost the most in terms of peak load. Secondly, an increase in overall energy consumption would be ideal for a T&D utility since they can then bill the customer for more energy usage. As seen in Figure 26, a smaller system uses more electricity over time than a larger one. Overall, T&D utilities prefer their customers use a smaller AC, as smaller systems have a reduced peak load but use more power over time.

The results of this study show that the homeowner's perspective is directly at odds with the utility's perspective. While homeowners favor larger AC systems, utilities find value in smaller capacity systems due to lower generation and peak load costs. While our NPC calculations have only considered initial investment cost and lifetime energy costs, the homeowner perspective could be influenced by utilities using financial incentives. For example, if the local utility experiences lower costs with a smaller AC system, the utility could provide incentives to the homeowner that make smaller systems financially more attractive. Since these smaller systems come with increased unmet loads, the incentive provided by the utility must be large enough to overcome the potential customer discomfort.

While our research suggests that subsidizing smaller AC systems would benefit the utility, this does not appear to be currently happening in the industry. The focus has been on increasing energy efficiency, where research has shown that switching from a SEER 13 system to SEER 15 increases annual energy savings by 20% and peak demand savings by 13% [91]. One industry example is that the Arizona Public Service Electric Company offers $245 to upgrade the efficiency of AC systems (SEER). Another local Phoenix utility, Salt River Project, subsidizes higher efficiency central AC systems by SEER for older homes. The subsidy is a rebate that grows with each increase in SEER, starting with SEER 15 for $200 [92] and ending with SEER 17 for $600. Interestingly, and in support of this research, the largest rebate is not for efficiency upgrades, but for purchasing a variable capacity system at $800. The more expensive but higher incentivized variable capacity system is most prized by the utility for its ability to lower their costs, most likely driven by the ability to lower the AC capacity during periods of high demand. In this research, variable capacity systems were not reviewed but may be a future option for determining and evaluating air conditioner subsidies.

Efficiency is a well-known method for lowering overall costs, but outside the scope of this study. However, we recalculated the Total Societal Cost (TSC) by adjusting for the 13% decrease of peak loads and a 20% reduction in electricity usage resulting from increasing an air conditioner's efficiency from SEER 13 to SEER 15. This efficiency improvement results in an average decrease in total societal cost of $85/year, though this does not include the extra capital investment for the more efficient AC system. Among set point temperature groups, the average TSC decrease ranged from $70-75/year and $85-108/year for the new and older homes respectively. On the other hand, utility costs (generation and peak load) are reduced on average by $105/yr and $140/yr for the new and old homes as SEER increases from 13 to 15.

The same calculation is possible for all scenarios in which the savings for the utility is greater than the cost to the homeowner. For example, there is no feasible incentive for the 70°F "Constant" scenario because homeowners would spend $75 more per year while the utility would only gain $30/year. However, if the homeowner's thermostat preferences are unknown, a more realistic incentive may be the average of all thermostat scenarios, as seen in the bottom row of Table 9. In that case the utility net benefits are $69/yr for the smallest system and they must incentivize homeowners above $30/yr or $325 upfront. These incentives are on a similar scale as the currently available $200-600 incentives for improving efficiency discussed previously. A win-win-win scenario for all stakeholders would be for the utility to offer incentives for smaller AC systems. Homeowners could then choose smaller AC systems and run them with setback schedules providing benefits for both the utility and society as a whole.

Utilities directly pay for Demand Response (DR) programs in order to encourage certain behaviors from their consumers. Such programs represent the maximum of what a utility is willing to pay. Within the context of this thesis, the T&D utility in Phoenix is the Salt River Project, an integrated utility that provides power generation, distribution and billing for Phoenix residents. They have one type of DR (Time Of Use) program, but it does not include controlling the power of a homeowner's AC system. Therefore, a different city's DR program will be discussed in order to demonstrate how the peak demand results presented here can be used to develop homeowner subsidies and other incentives. Peak demand of these AC systems is the only factor that would remain consistent outside of the bounds placed on the AC simulations presented here.

The following example demonstrates the value of peak load reduction and includes both demand response and peak load reduction initiatives. A massive Con Edison (ConEd) project called the Brooklyn Queens Demand Management program attempts to reduce power consumption, especially peak power consumption, for users in regions of New York City. ConEd is not an integrated utility and provides T&D services to the region. As ConEd publicly reported to New York State, their program has an average avoided cost of $179.52 per kW [93] from peak load avoidance since the project began. An example of generating an incentive from this information is as follows. If a consumer chooses a small AC system that has a lower peak power usage of just two kilowatts less than what they previously owned, ConEd values that smaller capacity system at about two times $179.52 per kW or about $360. Because that amount is saved by avoiding the larger system, ConEd can incentivize their customers by this amount. This region of the country does have higher costs than other areas, such as Phoenix. The avoided cost for ConEd is higher because building new transmission and distribution in the extreme urban environment like New York City is difficult.

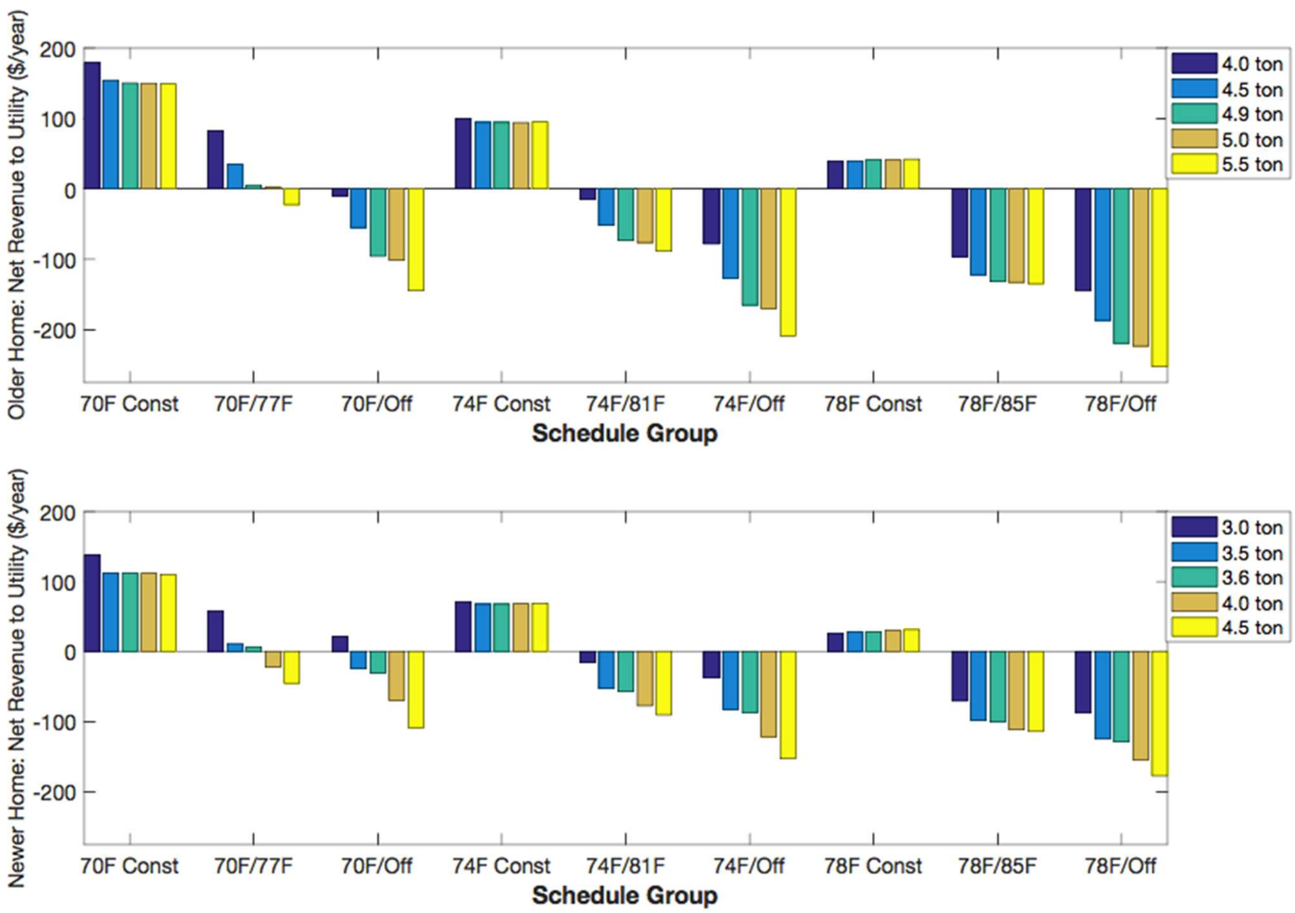

Figure 33: The net revenue to the utility per year expressed as the electricity sales minus peak load costs and minus generation cost (based on wholesale pricing)

If one AC capacity works better for the utility over another capacity, but costs the homeowner more, the utility must incentivize the homeowner to choose it. By adding how much the utility can save by switching to a smaller system from a larger system, incentives can be determined. Figure 33 shows the revenue of all 90 combinations to the utility per year. This value is the addition of negative peak load costs

(Figure 16) and negative generation costs (Figure 15) to the positive income from billing the customer for their energy consumption (Figure 11). Clearly, smaller systems are cheaper for the T&D utilities as they make more money as seen in Figure 33.

While utilities routinely subsidize more efficient AC systems, they may find it cost effective to also subsidize smaller systems or, more realistically, subsidize by the peak power consumption of a system, which would motivate both smaller and more efficient AC systems. To understand potential AC size incentives, Table 9 shows net cost to homeowners and net benefits to the utility across all scenarios (see Figure 33 for in-depth analysis).

Columns A and B of Table 9 are the net result of the electricity sales and the peak load and annual generation costs. Column (B-A) shows the value of the gain or loss. The loss is also the annualized potential incentive used to influence homeowners to choose the smallest AC system over the largest one. Columns D, E, and the final column are annualized costs of purchasing, installing and running the AC system. The final column shows how much more a homeowner pays due to choosing the smallest AC system over the largest one, and the least amount a homeowner would be willing to accept as an incentive, if they ignore other smaller system tradeoffs such as increased unmet load hours.

The simple calculations in the third (B-A) and final (E-D) columns show the revenue gain or loss of the utility and homeowner when the smallest system is chosen over the largest system. At a 70°F/“Off” schedule, homeowners would spend $18 more per year to own the smallest 4.0-ton AC rather than the 5.5-ton largest one, but the utility would gain $135/year. If the utility instead offered an incentive larger than $18/year to the homeowner to purchase the smaller system, the utility would save the difference. An upfront incentive of $195 (present value of $18/yr for 16 years at 5% discount rate) would cover the homeowner's loss while realizing savings of $117/yr for the utility. Across various schedules, the utilities have more to gain than what stand to lose homeowners when homeowners switch from larger to smaller systems. Therefore, incentivizing a switch is an option for utilities wanting to capitalize on the potential gain.

Table 9: The difference in net benefits of the smallest system over the largest system, for both the electrical utility and the homeowner.

AC Schedule	**(A) Cost/ Revenue to utility 5.5-ton ($/yr)**	**(B) Cost/ Revenue to utility 4.0-ton ($/yr)**	**(B – A) Utility gain using 4.0-ton over 5.5-ton ($/yr)**	**(D) Homeowner Cost 5.5-ton ($/yr)**	**(E) Homeowner Cost 4.0-ton ($/yr)**	**(E – D) Homeowner loss from owning 4.0-ton over 5.5-ton ($/yr)**
70°F Constant	149	179	30	1,284	1,359	75
70°F/Off	-145	-10	135	1,041	1,059	18
78°F /85°F	-135	-96	39	797	817	20
78°F/Off	-253	-145	108	732	735	3
Average of all AC Schedules	-63	6	69	963	993	30

Any incentives encouraging homeowners to decrease AC capacity is different than offering energy efficiency incentives because the utility will make more money off of increased consumption. Limitations to incentives are that utilities cannot know what a consumer is thinking. If a consumer planned to purchase a smaller system anyway, the utility would lose some money since they didn't need to incentivize. In this way, incentives are not always a motivator.

7.2.3 Society

The electric grid is overseen by various federal, state and local regulators. They influence industry subsidies, the energy market through oversight, and respond to environmental concerns, such as with the approval of new power plants. Ideally, regulators want electricity to be affordable for consumers and to decrease emissions in accordance with federal laws. They are also concerned with grid stability and resilience. Consequently, peak load management is often a consideration when examining new policies. Since the regulator's purpose is to do what is best for the common good, the Total Societal Cost (TSC) examined in this study were chosen to be the initial investment of the AC system to the homeowner, costs of peak load to a T&D utility, generation cost to the power generating utility, and social cost of polluting emissions. The annualized costs of each of these output metrics were totaled and are represented in Figure 37 as TSC. Specific issues for regulators include how to cheaply lower energy consumption and understanding energy savings tradeoffs to educate consumers. One of those tradeoffs, unmet loads, is not considered in the TSC, but their relationship can be seen in Figure 34 and Figure 35. These results also do not evaluate cost of transitioning to these scenarios, but do offer insight into which scenario may be worth investigating.

The TSC of an AC system shows an interaction effect between system size and thermostat schedule. While larger systems are always more beneficial to homeowners than smaller systems regardless of AC operation schedules, the same cannot be said when considering TSC. If a homeowner wishes to use a setback schedule, choosing a larger system that cools more quickly is the obvious choice to maintain comfort and minimize costs. However, this option can have a costlier TSC depending on the AC schedule chosen. Curiously, a larger system is the least costly for society if the homeowner will use a "Constant" schedule. The TSC would be lowest if homeowners used the smallest AC system with an "off" schedule, however, the homeowner would be sacrificing significant comfort.

The costliest combination was the 70°F constant setting with the largest capacity systems in the older home with a total $1,448/year and $1,132/year in the newer home. The Manual J calculation uses a 75°F constant schedule. The Manual J sizes for the old and new homes at the constant 74°F schedule, which is close to the Manual J calculation, was $1,266/year and $942/year. The current Manual J sizing standard is costing society an extra $118/year when sizing older homes and almost $200/year for homes built in Phoenix since 2010. As seen in Figure 38, the largest drivers of cost for all the scenarios were costs to the utility. Generation cost was collectively costlier than the second largest cost driver of peak load. Social cost of pollutants was minimal.

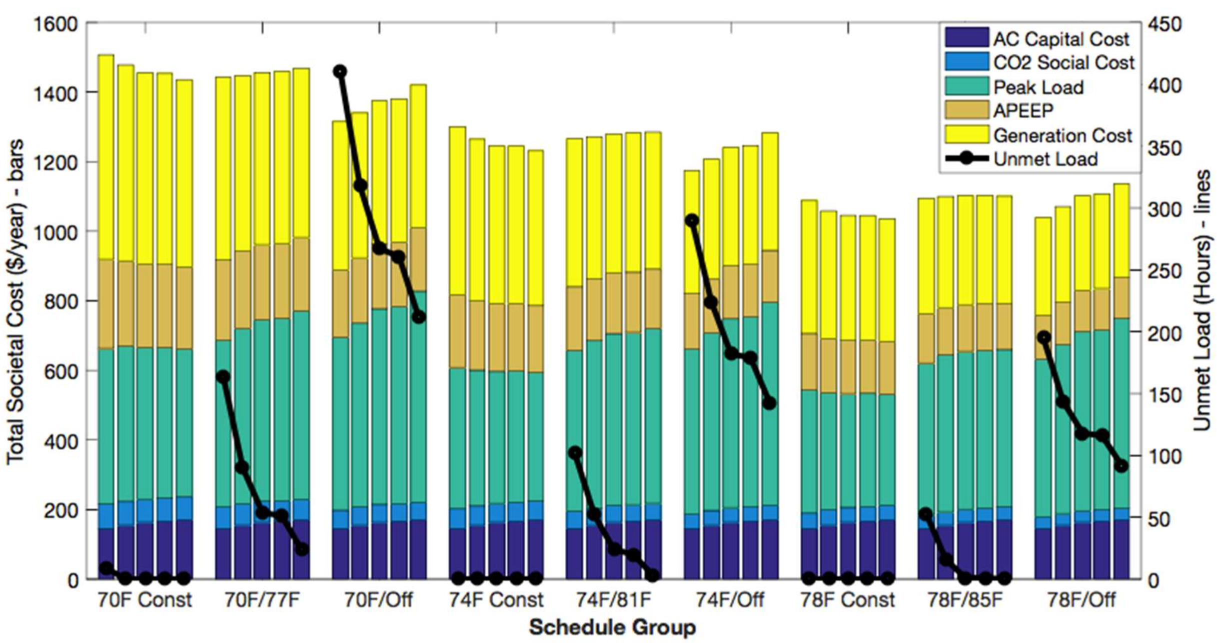

Figure 34: Total Societal Cost in the older home against unmet load hours.

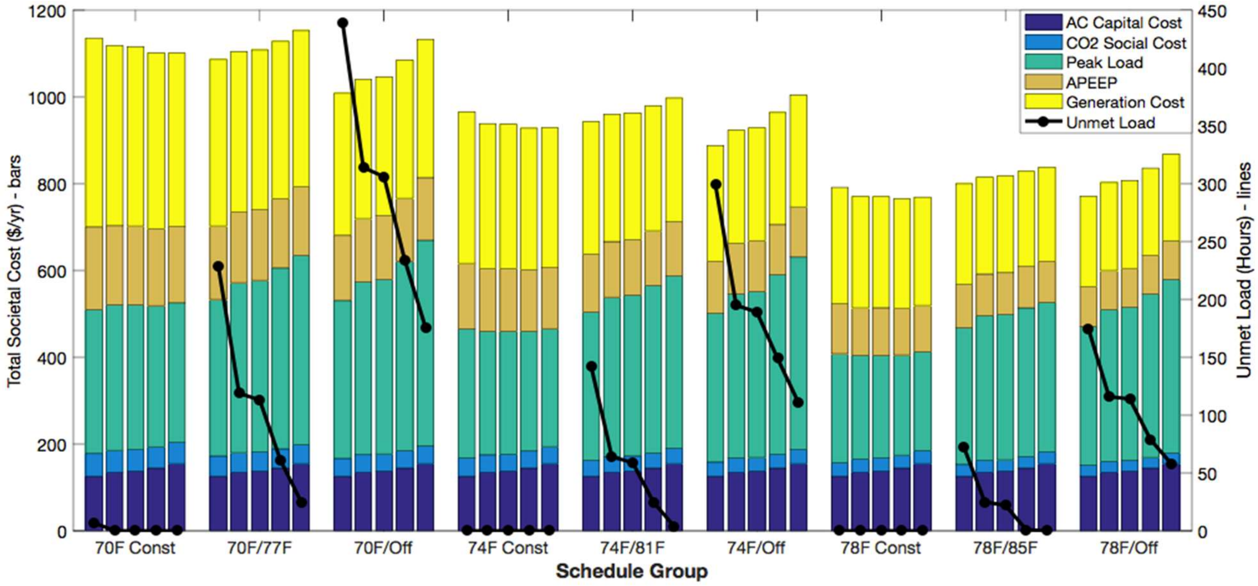

Figure 35:Total societal cost (bars) with unmet load hours (lines) for the newer home

Total societal cost (TSC) can be reduced by switching schedules. Literature advocates for thermostat schedules that involve a setback due to their lower electricity usage, reduced emissions and lowered homeowner costs. However, there are size-schedule combinations for which constant, or non-setback, schedules have the lowest TSC. For example, the 78°F "Constant" schedule is cheaper on average across all sizes than setback schedules within the same set point group. Although more expensive by $40/yr on average than the 78°F "Constant" schedule, the 74°F "Constant" schedule is also cheaper than the other size-schedule combinations within its set point temperature group. Switching schedules has similar effects on the social costs of emissions (EMC). This observation is important because switching thermostat schedules requires zero dollar investment by the homeowner, although certain schedules can increase the unmet load and sacrifice indoor comfort.

Although switching schedules can be helpful in lowering total societal costs (TSC), switching sizes within schedule groups can provide similar and often larger savings For example, switching from 78°F "Off" Manual J size system, to the EnergyStar recommended 78°F/"Plus Seven" setback schedule does not change the $1,102/yr of TSC. However, switching the Manual J size to the smallest size at the 78°F "Off" setting saves $63/yr in TSC and $7/yr for the 78°F/"Plus Seven" schedule. Overall, averaging TSC across all thermostat scenarios saves about $20/yr by switching from the largest to the smallest systems. The biggest difference between the smallest and largest capacities were about $100 within each schedule group, for both home types. For the older home, the smallest AC costs ranged from $925/year to $1,400/year, whereas for the older home they ranged from $704/year to $1,057/year. Since the trend in decreasing cost with decreasing capacity seemed unhindered, the absolute lowest cost capacity to society was possibly not modeled in this research. Although the homeowner would experience tradeoffs with unmet loads with even smaller systems, they are potentially mitigated by the inclusion of a smart thermostat. For both homes, the cheapest schedule types are the off schedules and schedules with higher starting temperatures.

8. Conclusions and Future Work

This research explored the costs and benefits to consumers, utilities, and society of changing the size of AC systems for homes in Phoenix, AZ. A study involving these stakeholders had not previously been performed in terms of central air conditioner selection and sizing. We believe the future of sustainability lies in individualized adaptations instead of generalized applications. This idea of an interdisciplinary approach was explored as all examined factors are flexible, depending on stakeholder priorities as seen in Table 10.

Table 10: Stakeholders and their individual priorities, which are either a output metric or part of a output metric examined in this study. The differences between each stakeholder lead to various tradeoffs between AC size and schedule.

Stakeholders	Homeowner	Utilities	Society	Total Societal Cost
Priorities	NPC	Peak Load Costs	Pollutants emitted	AC Capital Cost
	Unmet Loads	Generation Cost	Social cost of pollution	Generation Cost
	Electricity Consumption Cost	Electricity sales		Peak Load Costs
				Social Cost of Pollution

The results of each output metric considered in this study trended towards either larger or smaller capacity air conditioners across schedule groups. Various conclusions can be drawn from the output metrics plus their combined effect on society. Smaller capacity air conditioning systems have a slightly higher generation cost, but much lower peak load costs. They are cheaper for society, when considering costs that affect the common good. Larger systems on the other hand, have more output metrics with improved outcomes for the individual stakeholders. Not only do larger ACs use the lowest amount of energy and therefore customers are billed less for their AC use, but they also have the lowest NPCs. However, NPC is not always lowest with larger systems. Although true for both older and newer homes, as starting temperature increases, the lowest NPC tends to be with the capacities in the middle of the schedule groups. Larger systems also have lower unmet loads across schedules. Finally, they have lower emissions as well as associated social impact costs that consider impacts on human health and decreased recreational activity.

Although there are frequent warnings against oversizing central air conditioners, we found larger AC systems to be associated with lower generation costs, lower emissions and increased comfort for the homeowner at all thermostat schedules. Interestingly, AC system size choice was not clear from a societal perspective, as total social costs experienced an interaction effect with the thermostat schedule. For society, larger AC systems were preferred at constant thermostat schedules, while smaller AC systems were preferred when using setback schedules, although these preferences did not take into consideration customer comfort. While the most savings an individual homeowner had was about $290 over the lifespan of the AC system for owners of larger AC systems, the electric utilities find smaller systems most profitable. The smallest systems reduced costs by $75/yr per customer on average due to lower peak burdens and higher billing income. The Manual J standard size was infrequently the cheapest or most comfortable option. It also rarely influenced the collective costs for calculating utility incentives or societal optimization. Results for the two Manual J sized 3.6-ton and 4.9-ton systems were often close to other results, such as with the newer home net present costs or generated emissions. Rebate schedules were provided that would make smaller AC systems a net benefit to both utilities and homeowners. To provide a win-win-win situation for all stakeholders involved, this research suggests incentivizing homeowners to select smaller sized AC systems using rebates, using a setback (especially the "Off" setback) schedule, and to use a shorter eight-hour setback to reduce unmet loads.

While this preliminary work examines houses in Phoenix, Arizona, future work should look to expand these results to other parts of the United States and countries worldwide. What may be best for Arizona, may differ as electricity generation mix and weather vary across the country. Future work should examine these impacts, and should also consider indoor humidity when making AC system sizing recommendations for parts of the country where humidity is a concern. Humidity control is an important function of a central AC system. There is a concern that the larger systems would not provide the proper humidity control, one of the noted problems with sizing ACs over the Manual J standard. An improved understanding of the indoor humidity levels in humid climates is key since Off schedules were so often the cheapest choice. Arizona is not a humid climate and was chosen partly for this characteristic. Once research is performed to include the parameter of humidity, Manual J could be reexamined to lower costs to all stakeholders. To increase the relevance of these findings, examining schedules for various climates outside of Arizona to scale for larger populations is necessary. Finally, a life cycle analysis of the materials used in larger systems would better quantify the associated environmental and social impacts.

Equal weighting among all output metrics is not necessarily realistic. One improvement that can be made for future work is to weight output metrics to more accurately determine interactions, thereby improving the decision framework for homeowners in terms of their priorities. For example, if the homeowner values having no unmet loads over a certain amount of net present cost, the cheapest and most comfortable capacity and schedule combination would change.

Other future work would be to include more output metrics into the Total Societal Cost to provide a more accurate depiction of the best choice for all stakeholders. As previously mentioned, smart thermostats are increasingly entering the market. Since smart thermostat accounts for real time weather patterns to make a given AC tonnage work to its optimal performance, the best choices for each stakeholder may change with the use of a smart thermostat, as demonstrated in Section 7.1.2. In fact, calculating the optimal schedule for an AC system to turn on and off during the day to reduce loads during peak times would be useful.

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